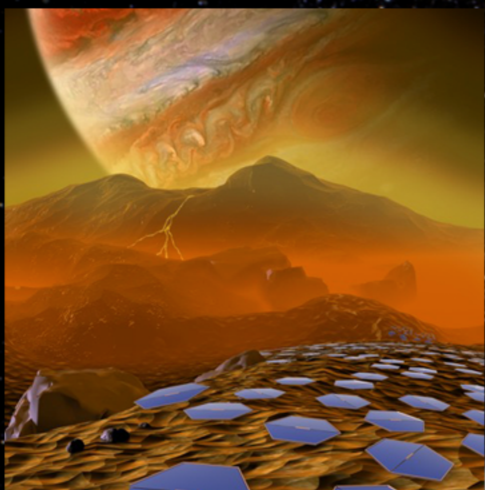
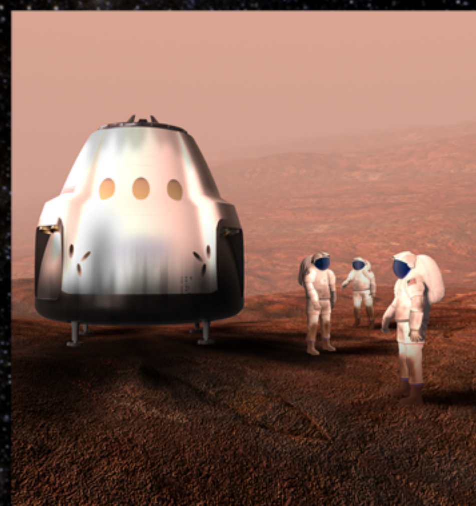
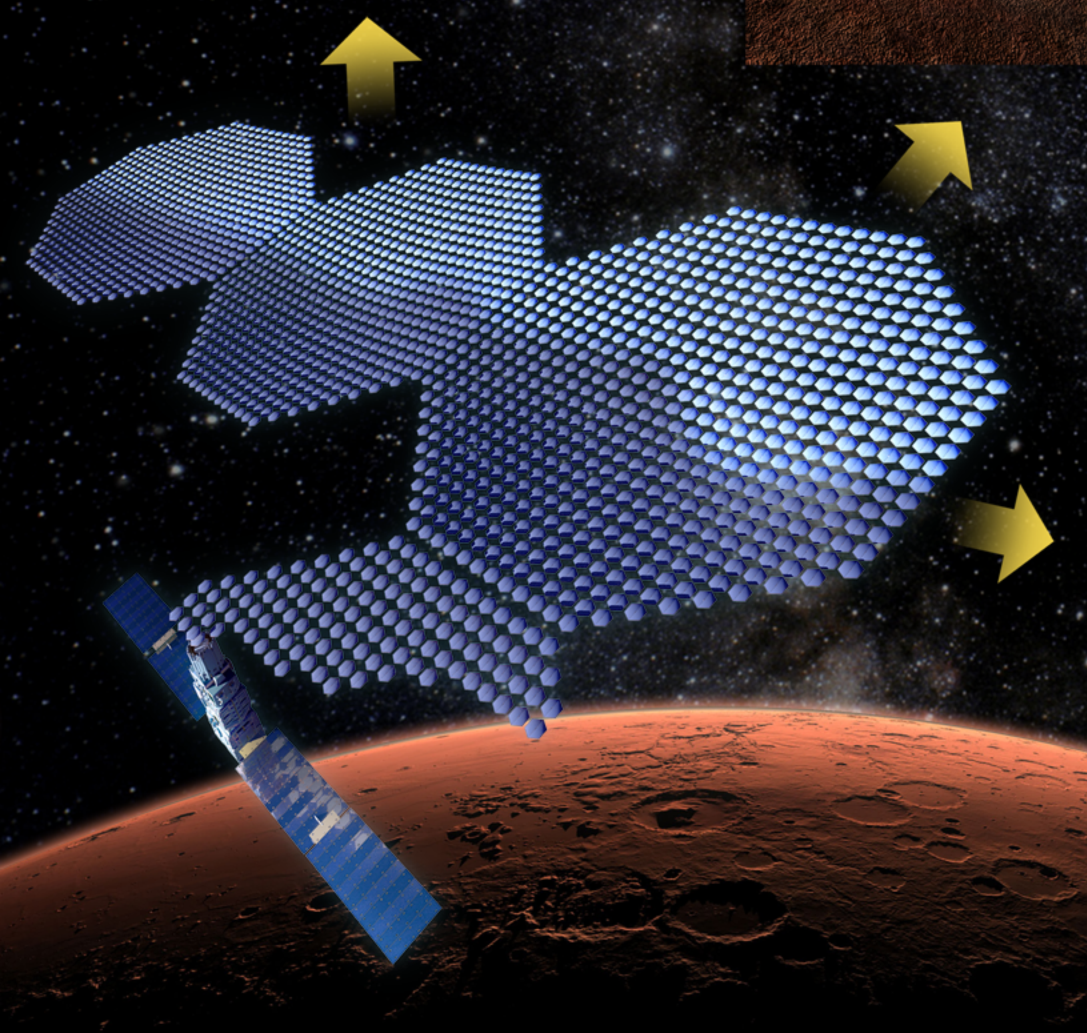
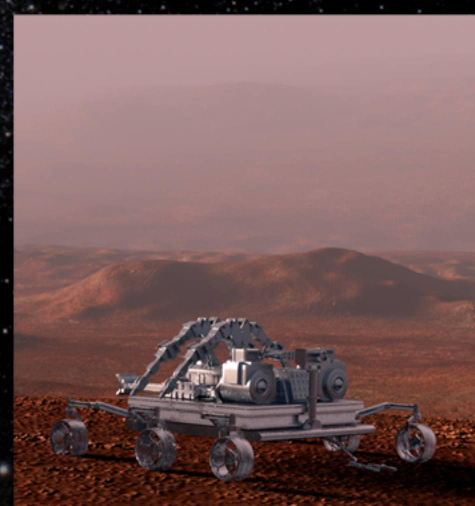
Adaptive Multifunctional Space Systems for Micro-Climate Control

Final Report









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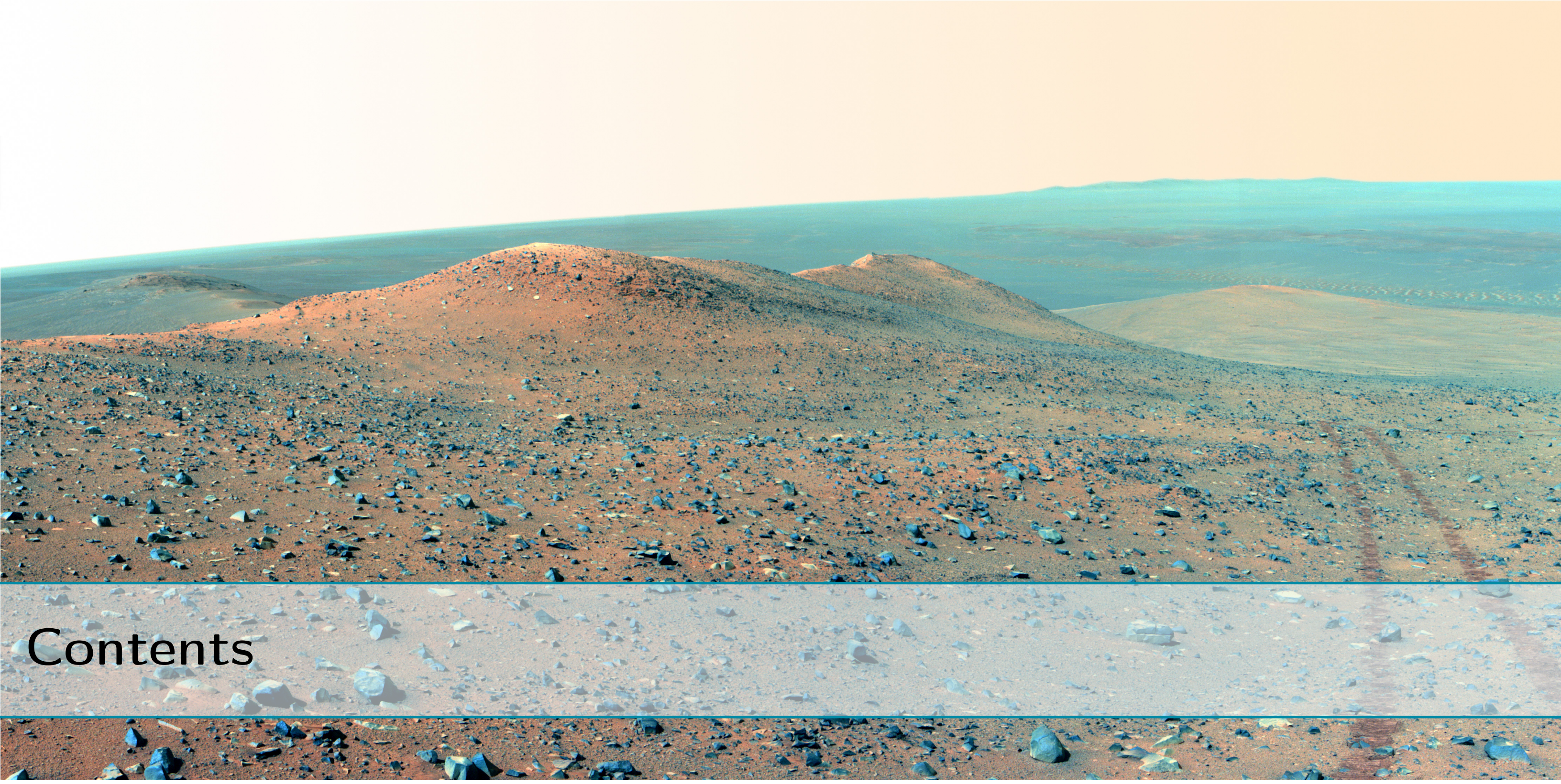
September 2015

In the last 3.85 billion years, the weave of mega-molecules called life has accomplished an astonishing feat: it has turned a hostile ball of stone green. It has transformed a planet of tempestuous climate and catastrophe into a garden. Now, life is poised to reach beyond Earth, to the Moon, Mars, asteroids, icy outer planet satellites—the possibilities abound. To take the first step toward achieving this goal, we need an energy infrastructure for the solar system. With multifunctional adaptive systems—modular networks with swarm intelligence—we can transform hazard and instability into resources and raw materials.

—Howard Bloom, Author and Study Participant



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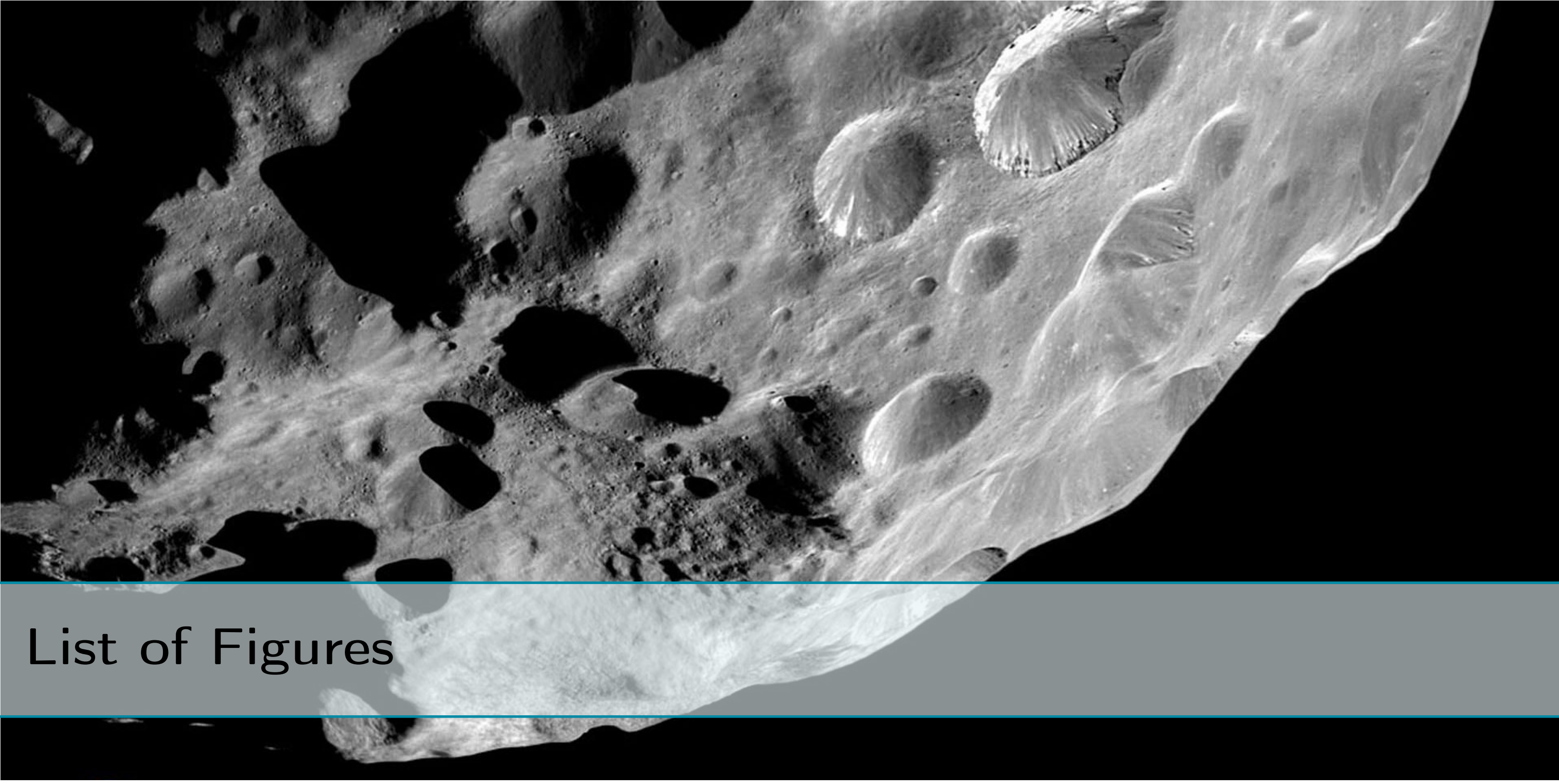

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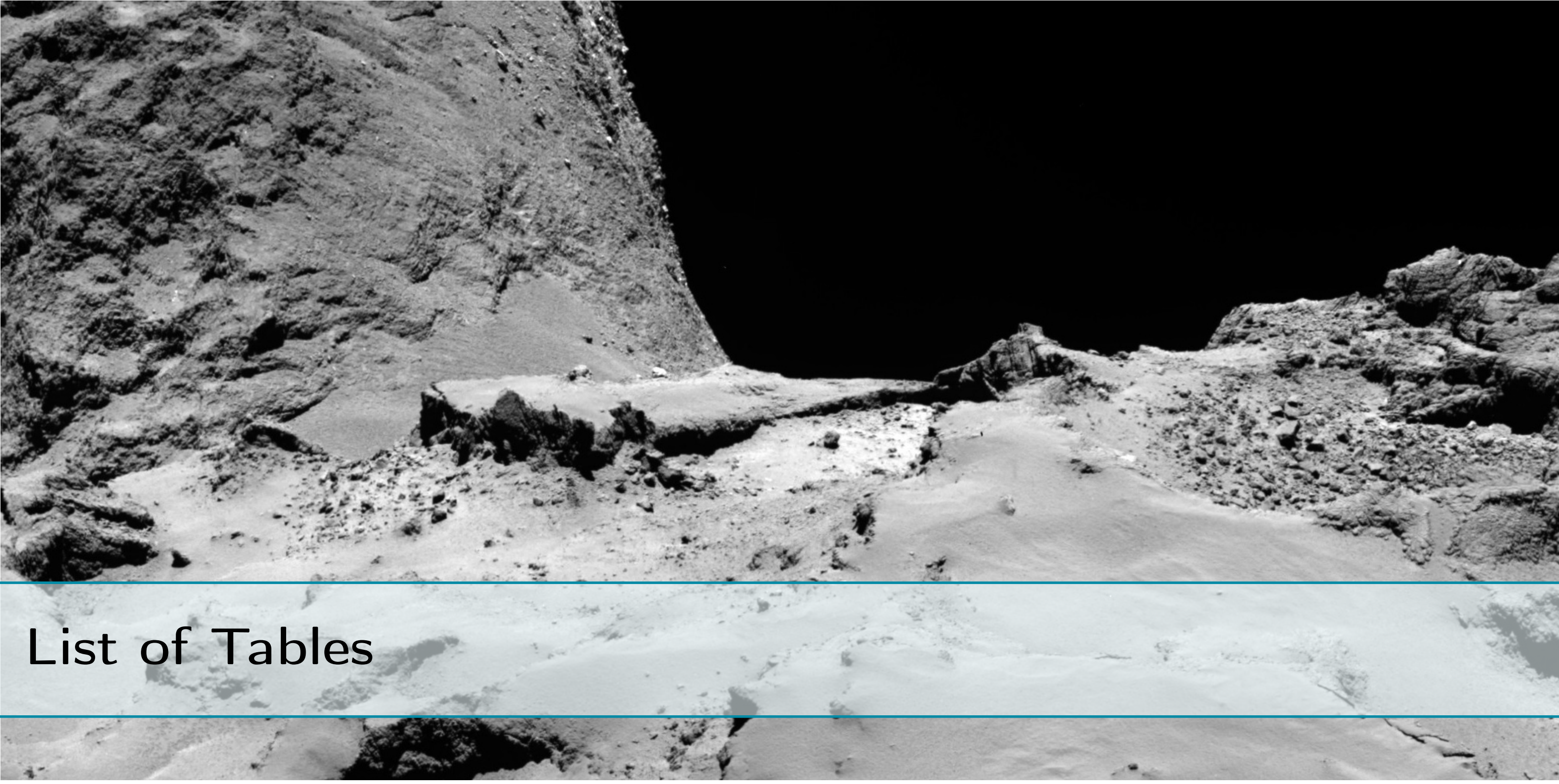

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Acknowledgements

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Thanks to all participants who attended the first and second workshops. Special thanks to James Edmondson and Howard Bloom for their effort, leadership, and dedication with respect to the topic of Smart Tiles, which emerged as a subtopic from the Study discussions and prompted conversations extending beyond the second workshop.

Special thanks also to Michele Judd, Prof. Tom Prince, and the Keck Institute for Space Studies staff for their continuing support.

Executive Summary

This report summarizes the work done during the Adaptive Multifunctional Systems for Microclimate Control Study held at the Caltech Keck Institute for Space Studies (KISS) in 2014-2015. Dr. Marco Quadrelli (JPL), Dr. James Lyke (AFRL), and Prof. Sergio Pellegrino (Caltech) led the Study, which included two workshops: the first in May of 2014, and another in February of 2015. The Final Report of the Study presented here describes the potential relevance of adaptive multifunctional systems for microclimate control to the missions outlined in the 2010 NRC Decadal Survey.[1]

The objective of the Study was to adapt the most recent advances in multifunctional reconfigurable and adaptive structures to enable a microenvironment control to support space exploration in extreme environments (EE). The technical goal was to identify the most efficient materials, architectures, structures and means of deployment/reconfiguration, system autonomy and energy management solutions needed to optimally project/generate a micro-environment around space assets. For example, compact packed thin-layer reflective structures unfolding to large areas can reflect solar energy, warming and illuminating assets such as exploration rovers on Mars or human habitats on the Moon. This novel solution is called an energy-projecting multifunctional system (EPMFS), which are composed of Multifunctional Systems (MFS) and Energy-Projecting Systems (EPS).

Specifically, the Study explored alternative solutions that might be able to revolutionize space missions through a dramatic increase in the ability to survive extreme environments, leading to:

[1] Committee on the Planetary Science Decadal Survey, National Research Council of the National Academies, Vision and Voyages for Planetary Science in the Decade 2013-2022, National Academies Press, Washington, DC, 2011.

- Innovative ways to redirect solar energy into shadowed exploration sites, enabling the exploration of permanently shadowed craters and caves, without use of radioisotope thermoelectric generators (RTGs)

- Innovative types of lightweight and multifunctional structures; with multiple advantages in packaging and deployment of space structures

- New types of robotic/autonomous systems, manufactured/printed in 2D, but morphing/shape-changing their 3D shapes

Such improvements in space robotic capabilities would offer a novel way of improving survivability in extreme environments,[2] facilitate new classes of missions, and open new frontiers of exploration and scientific discovery in relatively close-proximity destinations (Moon and Mars). They would enable mission operations that involve long periods of time without direct solar input at massively reduced cost; e.g., exploration of ice fields in permanently shaded craters and/or exploration of caves would become feasible in a context that otherwise requires RTGs.

One of the benefits of this initial effort has been to identify missions that would otherwise be too technologically challenging and/or expensive, in particular those that would involve long periods of time without direct solar input or RTGs, the availability of which may be limited in the future. The Study discussed permanently shadowed environments with remote deployables providing illumination, energy, and communications. Other applications that were discussed included: sun-shields to protect rovers from very strong solar illumination; thermal blankets to help them retain heat and survive a cold night; and calibration targets for instruments. This Study brought mission designers together with experts in these technologies, resulting in a better understanding of where we could best apply these ideas in space science, and leading toward focused development of the most promising concepts. The outcomes of the Study include:

- Identifying exploration/science drivers, and discussing examples of classes of missions facilitated by the energy-projection capability: solar concentration, light re-direction, and micro-climate generation/projection.

- Establishing fundamentals of key technology areas: materials/structures, packing/deployment, and adaptive hardware and software reconfiguration.

- Identifying technology gaps within each area, as well as areas of focus where further technological investment would be required, leading to the definition of a path for future research and development programs that would cultivate, mature, and apply these functionalities in order to enable the energy-projection capability.

[2] Kolawa, E. et al., Extreme Environment Technologies for Future Space Science Missions, Report No. JPL D-32832, September 2007.

1. Introduction

1.1 Motivation: An Energy-Infrastructure for Planetary Science

Extreme planetary environments represent the next frontier for in-situ robotic space exploration. Reconnaissance missions will be followed by robotic in-situ missions, and perhaps later by human exploration. All these mission designs have one common problem: harsh, extreme environments (EE), where temperature, radiation, and other factors render them infeasible at present. This Study explored an enabling capability for operation in EE, a solution applicable to all types of in-situ missions, which is to project and control a favorable micro-environment (e.g., around a rover) in the local area where exploration, exploitation, or human visits will take place. Multifunctional Systems (MFS) and Energy-projecting systems (EPS) not only transform the environment where they are needed, but they also adapt to needs by shape transformation. Their body surface can contain embedded reflectors and solar cells, and they can also carry antenna elements for communication, as well as actuation and control elements for shape change. This novel concept—providing remotely-controlled protection to the in-situ explorers of extreme environments by projecting and controlling an ameliorated micro-environment around them—has broad potential applications for both robotic and future human spaceflight.

EE may be characterized by low or high temperatures, high-radiation, high pressure, corrosive and toxic chemicals, etc. The EPMFS concept directly addresses the "Surviving Extreme Space Environments" Challenge, one of the NASA's Space Technology Grand Challenges,[1] specifically aimed at enabling robotic operations and survival in the most extreme environments of our solar

[1]NASA Space Technology Grand Challenges:
http://www.nasa.gov/pdf/503466main_space_tech_grand_challenges_12_02_10.pdf

system. In this Study, we have assessed the basic elements of micro-environment projection in EE in the context of various relevant mission scenarios. From a science perspective, the EPMFS concept will open new frontiers of exploration and scientific discovery in the Solar System. From a robotic control perspective, we will have studied controlled projection of sunlight on a moving target. The progress in shape-changing techniques will advance the field of origami robotics, paving the way to highly reconfigurable robots. From the materials and embedded electronics perspective, the integrated EPMFS fabric represents advancement over electronic fabrics, taking one step further their applications in smart clothing and smart homes and environments. From a systems perspective, this report is a preliminary feasibility assessment of the innovative multifunctional system integration for embedded materials, distributed sensing and actuation, and shape-changing. Solar concentration is also an area of promise for DOE applications. This Study contributes to multiple Technical Areas (TA) of the NASA Space Technology Roadmaps:[2]

- *TA04, Robotics and Autonomous Systems*: In all respects, EPMFS are a new class of robots/autonomous systems, built in 2D but reconfigurable to 3D shapes, with capabilities beyond the projections of the Roadmap.
- *TA12, Materials, Structures, Mechanical Systems and Manufacturing*: The Study addresses innovative types of lightweight and multifunctional structures.
- *TA03, Space Power and Energy Storage*: It proposes innovative ways to redirect solar energy into shadowed exploration sites.

1.2 Scientific Value of the Study

Recent scientific developments made a compelling case for the Study to be undertaken at this time.

Polar Craters on the Moon and Mercury

The discovery of ice deposits in permanently shadowed craters of Mercury[3] and the Moon[4] (see Figure 1.1) presents potential as a resource for both robotic and human spaceflight, but also a big challenge to mission planners. Such ice deposits preserve a unique record of the geology and environment of their hosts, both in terms of impact history (and possibly volcanic activity, if sufficiently ancient) and the supply of volatile compounds (mostly water), and so are of immense scientific interest. To date, these have only been studied indirectly (via remote analysis of impact

[2]NASA Space Technology Roadmaps: http://www.nasa.gov/offices/oct/home/roadmaps/

[3]Slade, M. A., B. J. Butler, and D. O. Muhleman (1992), Mercury radar imaging: Evidence for polar ice, Science, 258, 635–640, doi:10.1126/science.258.5082.635.

[4]Spudis, P. D., et al. (2010), Initial results for the north pole of the Moon from Mini-SAR, Chandrayaan-1 mission, Geophys. Res. Lett., 37, L06204, doi:10.1029/2009GL042259.

ejecta) and by remote active radar, but not in a manner that constrains reliably the depths of the deposits, their purity, or the structures within them. An EPS placed on a crater rim would facilitate modulation of the environment, making it less of a challenge for rover exploration. It would provide illumination for a considerable fraction of the year, enabling the use of passive remote sensing techniques. Intense focusing of the sunlight could melt or evaporate the ice, revealing the purity of the deposits, dissolved or suspended materials (e.g., salts, impact strata, other volatiles), and eliminate the need for a drill or other excavation tools. Additionally, the EPMFS-based communications antenna can potentially transmit science data back to Earth or an orbiting relay at a much higher data rate.

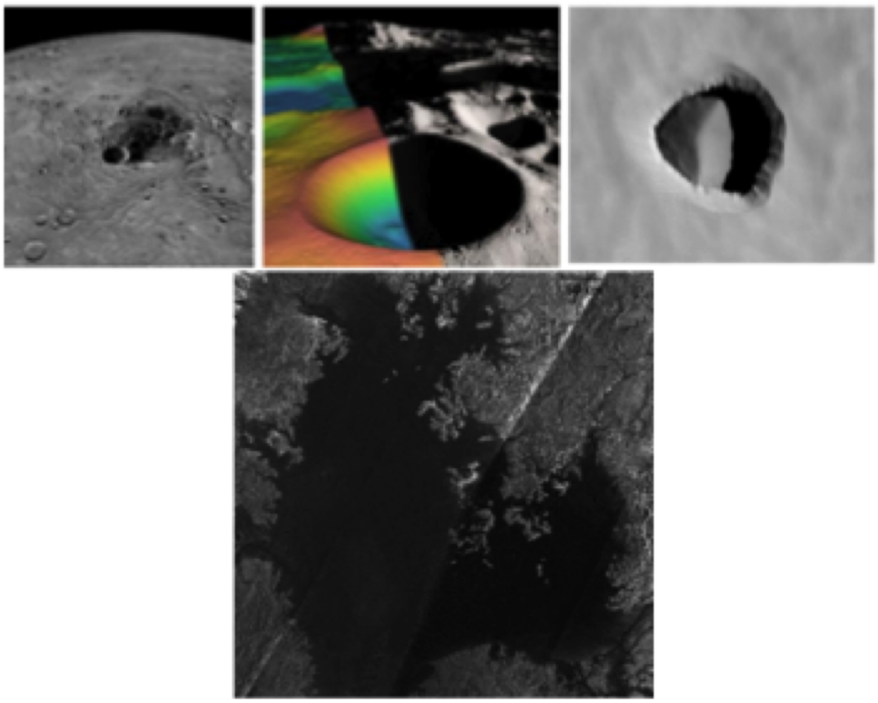


Figure 1.1: Mercury: ice-harboring craters near North Pole; Moon: synthetic photo of Shackleton Crater, potential candidate for lunar outpost; Mars: cave skylight near Arsia; Titan: Ligeia Mare.

Planetary Caves

Terrestrial caves host micro-environments on Earth, with unique and diverse biological communities. Recent discoveries of caves on Mars[5] and the Moon[6] provide intriguing new target sites for future missions. They may be the most viable habitats on Mars, for either endemic life, if present, or for human exploration. Not only do they protect from potentially-damaging radiation, but they can also host unusual thermal and chemical environments that could support ecosystem niches. An

[5] Cushing, G. E. (2012). Candidate cave entrances on Mars. Journal of Cave and Karst Studies, 74(1), 33-47.

[6] Haruyama, J., et al. (2009), Possible lunar lava tube skylight observed by SELENE cameras, Geophys. Res. Lett., 36, L21206, doi:10.1029/2009GL040635.

EPS placed outside of a cave entrance, or beneath a skylight, would be a particularly effective complement for a cave crawler mission, reflecting light into the cave system, providing many of the same advantages as discussed for shadowed craters, and serving as a communications relay.

Exploration of Venus

A variety of Venus missions have been proposed with very distinct science objectives.[7] The 2011 Decadal Survey includes an atmospheric-focused Venus Climate Orbiter (VCO) Mission based on a wind-driven balloon, a mini-probe and two drop sondes. The surface-centric Venus In Situ Explorer (VISE) mission would place a lander on the surface capable of sample acquisition and analysis with extended mission duration. The New Frontiers Surface and Atmosphere Geochemical Explorer (SAGE) mission would require an autonomous surface excavation system in an extreme environment (450°C, 92 bars) and in situ instrumentation for geochemical analysis. For all of these planned missions, efficient power and micro-climate generation technologies are required, and in the case of the Venus environment, the survival of the EPS itself also depends upon this technology.

Exploration of Titan

Scientific interest in Titan primarily stems from the presence of large amounts of organic compounds in its atmosphere and on its surface.[8] Figure 1.1 shows the Ligeia Mare on Titan. Features on Titan, such as volcanoes, sand dunes, lakes, and a nitrogen-rich atmosphere, are analogous to those on Earth. The solar flux at Titan's surface is on the order of 1 W/m^2, a value much too small to enable solar-powered vehicles. While nuclear power provided by radioisotope decay is the only electric power source in the foreseeable future, alternative options for power generation and re-direction need to be researched.

1.3 Relevance of EPMFS Technology to the 2012 NASA Decadal Survey

One potential mission scenario with associated technologies includes energy management of assets in craters on the Moon and Mercury and caves on Mars, where carrying an RTG would be extremely problematic. This application would drive technology development for deployables and multifunctional materials required to deploy on a crater rim or inside a cave.

A second potential scenario involves Sun-energy concentration and redirection from an aerostat for Titan assets, to avoid heavy on-surface assets and very complex thermal management in

[7] Venus Exploration Analysis Group Website, Presentations at Fifth Meeting of the Venus Exploration Analysis Group (VEXAG), May 7–8, 2008, Greenbelt, MD, available at: http://www.lpi.usra.edu/vexag/may2008/presentations/.

[8] Stofan, E. R., Elachi, C., Lunine, J. I., Lorenz, R. D., Stiles, B., Mitchell, K. L., ... & West, R. (2007). The lakes of Titan. Nature, 445(7123), 61-64.

a cryogenic environment. For Titan, an energy concentration capability is needed because the Sun is six astronomical units distant. Since the high density of Titan's atmosphere is extremely favorable to transportation by aerostat, this application would drive technology development for deployables and multifunctional materials combined with novel aerostat concepts and novel surface assets for in-situ sampling powered from the aerostat.

A third scenario involves Sun-energy concentration and redirection from a Mongolfière for Venus missions. Since clouds dominate the atmosphere, the energy transfer (from a high-altitude Mongolfière balloon) to power surface assets needs to be in a frequency band (for example, infrared) that can transfer through clouds. This application would drive new technology for deployables and multifunctional materials for energy concentration and redirection not in the visible band. Such improvements in space robotic capabilities offer a new way of improving survivability in extreme environments, enable new classes of missions, and open new frontiers of exploration and scientific discovery in several solar system locations. It also enables operations that involve long periods of time without direct solar input or RTGs, at massively reduced cost; e.g., exploration of ice fields in permanently shaded craters, and/or exploration of caves, would become feasible in a context that otherwise requires RTGs. Such missions are merely a subset of what could be achieved with the use of EPMFS.

In addition to the problem with availability of RTGs, there are technical and political problems involved with using these power sources, making alternate solutions desirable even with little or no improvement in mission performance. Further study is required to evaluate their utility in conjunction, for example, with landers on icy satellites in the more insolation-poor environments of the outer Solar System (e.g., Europa, Enceladus). However, it is anticipated that the leap in capabilities would be substantial, enabling major mass savings for instruments, power, and communication systems. Given the major interest in some of these hard-to-access extreme environments, it is necessary to develop these technologies now so that they are safe and proven for use in these compelling science missions.

1.3.1 Surface Landing Missions

Landing on Mars

Relevant future missions: Mars Sample Return (MSR), Mars NetLander, and future Mars rovers

Landing on Mars requires a fully autonomous system due to its highly dynamic environment, high gravitational forces, and atmospheric perturbations. With current technology, the divergence from the desired landing site at the end of the atmosphere entry phase is relatively large (e.g., 4–8 km at Mars) due to atmospheric perturbations. This large offset is one reason why missions require such large safe landing areas, within which they must subsequently "rove" to sites of scientific interest.

Landing on Bodies with Significant Gravity and No Atmosphere

Relevant future missions: Lunar South Pole-Aitken Basin sample return, Lunar geophysical network, Europa lander, NEO surveyor or explorer

Robotic landing on large surfaces without atmosphere (e.g., the Moon) is less challenging than landing on Mars. Atmospheric uncertainties are not present and the target site is visible starting from very high altitudes with no entry "plasma phase" to block the view.

> ***Europa Lander.*** Studies of a Europa lander were conducted by JPL as part of a Europa option study completed earlier in 2012. The lander option was ruled out as too costly in the current environment. However, it was recognized that a future Europa lander is important and that more information about the surface will be needed to design the lander. Accordingly, the Europa Clipper mission, consisting of multiple fly-bys, will be equipped to perform landing site characterization. This future lander mission will require advanced capabilities in the areas of efficient operations, sampling, and potentially deep drilling, all using radiation-hardened technology.

Surface Landing on Low-Gravity, Small-Body Targets

Relevant future missions: Comet surface sample return, NEO reconnaissance, planetary defense, martian moon exploration

Low-gravity landing differs fundamentally from high-gravity landing in time-scale and the requirement for high thrust, as well as in the need for closely operating trajectory and attitude-control loops. Many missions to low-gravity targets will make multiple landings, and so will require landing and ascent capability. By definition, an atmosphere is not an issue at these targets, and with all "airless" landings, visibility of landmarks on the surface is continuous (if lighting is appropriate). An important characteristic of these missions is the lack of *a priori* information about the body. In particular, detailed maps will be required to undertake the landmark-based navigation (target-relative navigation, or TRN) as well as detailed gravity models. In general, this requires an extensive ground campaign to develop these maps in a process that can be highly labor intensive.

> ***Near Earth Objects (NEOs).*** This class of missions would investigate NEOs for general planetary science purposes, for planetary defense purposes, for pre-mission surveys, and reconnaissance for human exploration and retrieval. These missions will share characteristics of other small body missions, including the need for autonomous surface guidance, navigation, and control (GN&C), precise global localization, small body mobility, and sample collection and handling. If surface contact is going to be made, precision sample collection and handling subsystems will be required (touch-and-

go (TAG), darts, harpoons, and others), which will also require interaction with the surface regolith.

Initial planetary defense missions such as Planetary Defense Precursors (PDPs) will explore alternative defense strategies. These may be small investigatory surveyors to assess physical characteristics of the small body and leave precision-clock-based radio beacons for precise global localization and/or mitigation technology demonstrations incorporating one or more deflection methods, such as electric propulsion (EP) systems or gravity tractors. Such missions will share the entire surface technology needs of the sample return missions.

Many future small body missions are likely to be micro-spacecraft missions. Aside from the already-discussed technology requirements associated with small body missions in general, micro-missions will require specialized micro-spacecraft subsystems. Because of the small, compact, and inexpensive nature of micro-missions, these spacecraft will likely need more extensive autonomous capability than simple TAG functions, including better ways to manage operations, and to handle samples collected from different locations.

Landing on Venus

Entry trajectories on Venus, after deceleration to subsonic speeds, are very slow, with simple parachutes providing decent paths of many tens of minutes' duration. A variety of Venus missions have been proposed with very distinct science objectives, mobility systems, and GN&C requirements. The 2011 Decadal Survey includes an atmospheric-focused Venus Climate Orbiter (VCO) Mission based on an uncontrolled wind-driven balloon with global localization needs. In addition to the balloon, there is a mini-probe and two drop sondes.

Landing on Titan

As for Venus, entry trajectories on Titan, after deceleration to subsonic speeds, are very slow, with simple parachutes providing decent paths of many tens of minutes' duration. There are two potential missions to explore Titan via different mobility systems: 1) based on a wind-driven Montgolfière, and 2) based on a lake lander. The Titan Saturn System Mission (TSSM), in which a wind-driven Montgolfière is used to survey the moon, and a lake lander is used to explore the methane and ethane lakes, require unique localization capabilities, assisted by efficient operations, and a sophisticated set of technologies in the areas of aerial mobility (for the balloon) and surface mobility (for the lake lander). All these capabilities will also need to rely on high-performance computing hardware and software, particularly in the path planning and management and correlation of science data collected by heterogeneous sensors.

On the other hand, alternative mission concepts using passive elements such as floaters will not likely require precise localization. In general, all balloons require localization, but balloons operating near the surface require even higher levels of precision to avoid collisions and acquire surface samples from small terrain features. There is a range of possible Titan balloon missions going from uncontrolled, all-passive, helium, super-pressure balloons to sophisticated motorized blimps. There is a corresponding range of GN&C requirements associated with this aerial mobility. Besides a lander and an orbiter, the TSSM includes a hot air balloon (Montgolfière) that might require a vertical ascent/descent control system and accurate localization ability. More advanced versions of this balloon are possible in which the balloon changes altitude to catch favorable winds and go to desired locations above the ground. This wind-assisted navigation was not part of the original TSSM, but is a logical extension. Also, it is an example of the impact of GN&C technology on a mission on a planetary scale, since innovative mission planning strategies for long-duration flights might have to be developed while keeping in mind the limited lifetime of vehicle resources.

Finally, challenges common to virtually all planetary science missions beyond the orbit of Mars include limited bandwidth and high-latency communications, which preclude real-time teleoperation, thus requiring a high degree of autonomy and reliability.

1.3.2 Proximity Operation at Low-Gravity, Small-Body Targets

Relevant future missions: Comet surface sample return, Trojan asteroid tour and rendezvous, martian moon exploration

Key characteristics of small-body targets are lower gravity and lack of atmosphere. The low gravity allows for 1) longer timelines for surveillance and characterization of the target site, 2) gradual descent to the target, 3) multiple landings or contacts and ascent, and 4) aborting and restarting during critical activities. The lack of atmosphere removes uncertainties due to atmospheric and wind effects, and provides a clear scene for landmark-based autonomous navigation with TRN and closed-loop GN&C, except in the case of comets, which produce an outgassing atmosphere that at times can be substantially obscuring. Controlling the spacecraft to avoid contact with the surface during proximity operations is one of the critical requirements for this mission type. Additional challenges may arise from forces due to ejected material and gas. Unknown and complex gravity models and dynamics of the target body are effective perturbing forces that must be countered, while still maintaining landing accuracy and safety. Science requirements to avoid disturbing or contaminating the surface with propellant often add severe GN&C constraints that must also be overcome.

A key dynamic attribute of such missions is "terramechanics," that is, interaction with surface material that can vary in strength and density by orders of magnitude between asteroids and comets.

Multiple forms of proximity operations and surface approaches are under examination, including touch-and-go (TAG); open-loop close flyby; and harpoons, darts, and others. These share, in various combinations, phases of operation including approach, descent, hovering, ascent, pursuit, and capture.

These missions also present important autonomy challenges, especially for failure detection, isolation and recovery (FDIR) functions. For scenarios where the spacecraft is close to the surface of the body, a few moments of faulty attitude maintenance can end the mission, driving a solar array into the regolith or breaking an appendage. Therefore, more effective and reliable FDIR logic must be incorporated into the executive functions to provide varying levels of fallback, regroup, recovery, or simple escape from the region of danger. Such logic may also, in the case of active comets, need to assess the danger associated with the active body itself.

1.3.3 Sample-Return Missions

Sample-return missions from the different targets in our Solar System may take one of several forms, all requiring advanced GN&C skills. As currently envisioned, Mars Sample Return (MSR) will loft a sample into orbit from a surface rover, requiring the capturing craft to perform autonomous rendezvous and docking (AR&D) operations. A primitive-body sample return might require a TAG operation that is in some ways a very soft landing, with an immediate ascent, featuring the challenges of a low-gravity lander, plus other challenges associated with a brief grazing contact. This is the approach to be taken by the Osiris ReX mission, currently in development. Other sample return missions may be MSR-like, with direct-to-Earth return, requiring onboard navigation ability to achieve a highly fuel-constrained return trajectory. Still others may use dart-like projectiles to mechanically take a sample and eject it back toward the waiting spacecraft, requiring an MSR-like AR&D operation. Some have proposed micro-sample-return missions to NEOs or other asteroids, or even to martian moons, where MiniSat or CubeSat-class vehicles would return samples to the Earth or Moon via micro-electric propulsion. Such missions would likely require highly reliable interplanetary autonomous navigation, because communication with the spacecraft in deep space would be impracticable.

Mars Sample Return (MSR)

Both the roving/sample gathering and caching segment, as well as the cache retrieval/Mars Ascent Vehicle (MAV) launch segments of a potential Mars Sample Return (MSR) mission, would contain substantial requirements for new surface GN&C technology. The need to collect samples from a rich and diverse set of well-characterized sites within a limited mission duration requires faster and more energy-efficient rover navigation. Better prediction of vehicle mobility via improved terrain sensing will advance mission safety and enable operation on more extreme terrains. When combined with methods to plan under uncertainty, quantitative measures of the uncertainty associated with terrain sensing and predicted vehicle mobility will facilitate more efficient operations, improve mission safety, and potentially enable access to more challenging terrain. Improvements in global localization will enable greater leveraging of orbital data in traverse planning, thereby supporting more efficient long traverses. Sampling acquisition and handling methods need to be matured and updated based on more demanding mechanical designs and constraints.

Comet Surface Sample Return (CSSR)

The New Frontiers Comet Surface Sample Return (CSSR) mission is one of several potential missions to small primitive bodies. There have been prior cometary missions beginning with the European Space Agency's (ESA) Giotto (fast flyby) and continuing with ESA's Rosetta mission, which rendezvoused with a comet and placed a lander on it in 2015. Many of these new missions will require technologies such as touch-and-go (TAG), a type of autonomous rendezvous and docking GN&C system that can make close, controlled approaches and gentle contact with the rotating surface of the body, or different types of penetration systems such as harpoons, darts, or drilling end-effectors. Since ground testing of systems operating in microgravity is extremely costly, innovative approaches for integrated modeling and simulation of proximity operations will be needed to test system performance. Similar to the MSR mission, CSSR will require advances in the areas of sampling and sample handling, efficient operation methodologies, precise global localization, and advanced options for surface mobility in the cometary microgravity environments.

Lunar Sample Return (LSR)

The Lunar South Pole-Aitken Basin Sample Return is another potential New Frontiers mission. A soft landing on the Moon, probably in rugged terrain to ensure a sampling of material from the mantle, will require several novel surface GN&C elements. These include vision-based Target-Relative Navigation (TRN, landmark modeling and tracking), fast and energy-efficient roving capability, precise global localization, efficient operations, advanced sample collection and sample handling capabilities, and automated path planning and optimization.

1.3.4 Multiple-Target Planetary Tours

Relevant future missions: Titan, Enceladus, and Saturn system mission, Europa orbiter/lander

A multi-target solar-system tour (e.g., of asteroids) is likely to be a low-thrust mission, and require some onboard ability to cope economically with the intense activity of electric propulsion over long cruise times. If the tour is of a multi-moon system of one of the gas giants, autonomous path planning and targeting will be necessary to accurately target mission-critical keyholes that are typically low-altitude points above the moons. To achieve the necessary accuracy, landmark-based autonomous navigation with TRN will be required. To increase data return while reducing downlink requirements, autonomous systems to plan, schedule, implement, and reduce science data linked to onboard GN&C will be advantageous.

1.3.5 Planetary Orbiters

Relevant future missions: Jupiter Europa orbiter, Uranus orbiter and probe, Io observer

Though planetary orbiters have been successful without extensive autonomous onboard GN&C, future missions with more demanding requirements will feature such systems. With landmark- and TRN-based autonomous onboard GN&C, orbiters can maintain their own orbits. At Mars, autonomous aerobraking will save considerable operations costs. Autonomous aerobraking systems are closely related, if not identical, to autonomous onboard GN&C systems. Autonomous navigation, combined with automated event planning and sequencing, will greatly aid the mapping of bodies, or the high-resolution targeting of specific locations, or even the identification and targeting of newly arising features of interest. For orbiting or flybys of planetary targets with high radiation (e.g., Europa), innovative GN&C sensor/actuator technologies and shielding approaches should be augmented with algorithms that can maintain healthy GN&C solutions in the presence of radiation-induced hardware anomalies. System-level trades of individual hardware performance, integrated algorithmic and system design solutions, and traditional shielding options will lead to optimized flight system and mission-level design for these very challenging missions.

1.4 Technological Challenges in the NASA Space Technology Roadmap

This section excerpts pertinent top technical challenges and high-priority technologies from the recently-released document, *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*,[9] henceforth referred to as the Roadmap. The intent is to provide convenient access to the Roadmap to better illustrate the commonalities and differences between that even broader analysis and this report.

As indicated above, besides contributing to multiple Technical Areas (TA) of the NASA Space Technology Roadmaps:[10], i.e.: *TA04, Robotics and Autonomous Systems*, *TA12, Materials, Structures, Mechanical Systems and Manufacturing*, and *TA03, Space Power and Energy Storage*, the ideas discussed in this report have relevance to applications of potential interest to the Department of Energy, as well as the Department of Defense. The Air Force and the Army have been interested in multifunctional systems for some time. Also, the Department of Energy, with the SunShot Initiative, has been making progress in innovative solar energy concentration systems.

[9] Steering Committee for NASA Technology Roadmaps, National Research Council of the National Academies, NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, National Academies Press, Washington, DC, 2012.

[10] NASA Space Technology Roadmaps: http://www.nasa.gov/offices/oct/home/roadmaps/

1.4.1 Multifunctional Structures, Materials, and Systems

This section has been excerpted from the NASA Technology Roadmap, TA03 and TA12, as well as from the AFOSR presentation on Mechanics of Multifunctional Materials and Microsystems, 5 March 2014.

The multifunctionality implies coupling between structural performance and as-needed functionalities (e.g. electrical, magnetic, optical, thermal, chemical, biological, and so forth) to deliver dramatic improvements in system-level efficiency.

Fundamentals of mechanics for "multifunctional design":

- Multi-scale simulation
- Interfacial phenomena
- MEMS
- Poro-vascular composites
- Electronic damping
- Load-bearing antennas
- EM tunable fluids
- Integrated circuits

Design of "autonomic" structures which can sense, diagnose and respond for adjustment with minimum external intervention:

- Damage detection
- Neurological system-inspired sensory network
- Self-diagnosis
- Self-healing
- Regeneration/remodeling
- Plant-mimetic cooling
- Variable thermal conductivity structures
- Nano-lattices

- Micro-vascular thermal management

Design of "adaptive" structures which allow alteration of shape, functionality and mechanical properties on demand:

- Mechanically-adaptive materials
- Artificial muscles
- Programmable materials
- Thermally activated reconfigurable systems
- Muscular-skeletal system-inspired morphing structures
- Metamaterials with local resonance

Structural integration of power harvest/storage/transmission capabilities for "self-sustaining" system:

- Energy harvesting textile composites
- Structural batteries
- Hybrid energy harvesting systems
- Integrated solar cells for UAV wings

Design, manufacturing & durability of "multifunctional materials":

- Compliant nano-spring interfaces
- Biomolecular cells for sensing and actuation
- Damage-tolerant biological composites
- 3D printed composites

Transformational opportunities:

- Electronic composites for load-bearing/conformal/tunable antennas. Ruggedized UAV antennas of reconfigurable frequency response.
- Structural materials with self-healing, regeneration/remodeling, self- strengthening and in-situ repair capabilities. Quantum improvement in survivability of aerospace structures.

- Structural micro-vascular composites for continuous self-healing and self-cooling systems. Quantum improvement in survivability & autonomic thermal management of aerospace structures.
- Neurological system-inspired sensing/diagnosis/actuation network. Autonomic state awareness in aerospace.
- Muscular-skeletal system-inspired adaptive structures using active, reconfigurable and programmable materials. Next generation morphing wing aircraft.
- Structural integration of power harvest/storage/transmission capabilities. Self-sustaining UAV and hybrid-powered aircraft.
- Stimuli-responsive biomolecules for sensing/actuation. A new class of transducers.

1.4.2 Energy Storage and Power

This section is excerpted from NASA TA03.

Many NASA missions (cross-cutting) would benefit from the mass reduction resulting from the use of multifunctional structures in the power systems. The idea of incorporating power system elements into the structure of a vehicle or habitat would be beneficial in reducing weight and could also enhance reliability and safety through enhanced capability for redundancy. Current structural elements are not electrically active. However, if power system components and structural elements were designed together in a system with part of the power system providing the structure, or part of the structure providing a power system function, it would be possible to provide "dual use" elements in place of current "single purpose" elements.

One concept would involve using the space/aircraft structure as the electrode materials for batteries. The electrolyte could be sandwiched between two electrode plates, which would be part of the structure. This would require the electrodes (anodes and cathodes) to have sufficient strength to bear structural loads. This is clearly possible with the advancement of nanotechnology. For example, carbon nanotubes incorporated in electrodes could provide the strength. The opportunities would probably be greater for a multifunction? al structure incorporating super capacitors. Boron nitride (BN) nanotube-based super capacitors are currently of great interest. The structure can be strengthened by BN nanotubes, which can also be used as super capacitors for energy storage. Another possibility is to use the structure as the main power bus bar where the power could pass through the structure and could automatically find the path of least resistance and could "heal" itself if damaged. In effect, it could be a "smart structure."

For a multifunctional structure incorporating super capacitors, it would be necessary to first demonstrate concept feasibility (to TRL 3) in three years, complete subcomponent testing in six years and provide a concept demonstration in ten years. For multifunctional materials that can bear load and act as electrode materials, initial materials could be developed in five years, then a structural sub-system demonstrated in six years and a system level demonstration performed in 10-12 years. Also, nanotube-based super capacitors will provide novel high energy density future energy storage capability as well as being excellent candidates for inclusion in multifunctional structures.

1.4.3 Structural Systems

This section comes from NASA TA12.

For deep space missions, a paradigm shift similar to the change from a few day Lunar mission (Apollo) to a multiple year low earth orbit habitat (Space Station), will be a necessary requirement. This means lighter weight, more compact, more autonomous, capabilities must be developed to enable not-too-distant future deep space missions. A suite of such enabling structural technologies is presented in Figure 1.7. The focus of these technologies is more system integration and more autonomy while reducing mass and volume. Examples of the subject technologies include a research project demo of a lightweight composite tank, and a metallic foam sandwich panel where hypervelocity Micrometeoroid on Orbit Debris (MMOD) impact capability is integrated into the structure.

1.4.4 Robotics and Autonomous Systems

The roadmap for TA04 consists of seven technology subareas: sensing and perception; mobility; manipulation; human-systems integration; autonomy; autonomous rendezvous and docking (AR&D); and robotics, tele-robotics, and autonomous systems engineering. TA04 supports NASA space missions with the development of new capabilities, and can extend the reach of human and robotic exploration through a combination of dexterous robotics, better human/robotic interfaces, improved mobility systems, and greater sensing and perception. The TA04 roadmap focuses on several key issues for the future of robotics and autonomy: enhancing or exceeding human performance in sensing, piloting, driving, manipulating, and rendezvous and docking; development of cooperative and safe human interfaces to form human-robot teams; and improvements in autonomy to make human crews independent from Earth and make robotic missions more capable.

For the TA04 roadmap to describe and provide supporting text for each of the level 3 technologies (like the other roadmaps), it would have to be largely rewritten, and the panel made a number of suggestions for changes to TA04 for it to parallel the other roadmaps. As a result, the steering committee and responsible panel did not have a list of well-defined technologies originally identified in the draft roadmaps, and have recommended a new set of level 3 technologies.

Table 11. *WBS # 2.2.5 Innovative, Multifunctional Concepts*

TECHNOLOGY PRODUCT Key Technology/Challenges	What it Enables/Primary Mission Support	TRL/Current Status	Steps to TRL 6
a. Integrated Cryo Tank Address competing thermal isolation and strength/stiffness issues. Integrating primary load paths (especially at joints) Cryotank/sensor integration.	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /All Missions	TRL2, Technologies exist individually to differing levels of maturity, but not developed as a system.	Demonstration of capabilities with a prototype cryo tank.
b. Integrated non-pressurized (MMOD) Manufacturing scale up. Incorporate appropriate MMOD requirements and capabilities.	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /All Missions	TRL2-3, In development stage, though some of the technologies exist individually.	Prototype of MMOD shield for Cryo Fluid transfer project (SOMD proposal).
c. Reusable Modular Components Modular design without undue weight penalties.	Lower life cycle cost. Lower launch mass. Provides flexibility with spares and maintenance. /All Missions	TRL 2+, depends upon application Some Systems studies for lunar-based architecture have been published.	Depends upon application, Demonstrations of full-scale and subscale prototypes in a laboratory environment.
d. Integrated Windows Maintaining Optical Quality with new materials. Integration of windows system into structure.	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity./Human Space Flight/Habitable Modules	TRL 2-5, Multi-center effort is in progress for materials development at risk for continued funding (see Materials section). Incorporation into structure depends upon outcomes.	Prototype for a DRM with Prototype windows.
e. Active Control of Structural Response Accurately modeling a full scale structure. Providing controls without adding undue weight.	Flexibility of structural design and improved safety in aggressive flight environments. Reduce system mass. /All Missions	TRL 2-5, Depends upon application. Some load alleviation systems are in use in aircraft. Some heavy systems have flown in satellite applications.	Depends upon application, Demonstrations of full-scale and subscale prototypes in a laboratory environment.
f. Integrated Pressurized (MMOD, Radiation, Permeability) Address competing system requirements. Integrating primary load paths (especially at joints)	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /Human Space Flight/Habitable Modules	TRL 2, In development stage, though some of the technologies exist individually.	Demonstration of capabilities with a prototype structure and a TBD DRM.
g. Integrated Pressurized Structure with Thermal Control Address competing system requirements Integrating primary load paths (especially at joints) (thermal management integrated into technologies in 2.2.5f).	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /Human Space Flight/Habitable Modules	TRL 2, In development stage, though some of the technologies exist individually.	Demonstration of capabilities with a prototype structure and a TBD DRM.
h. Integrated Non-pressurized Structure for High Temperatures Address competing thermal isolation and strength/stiffness issues. Integrating primary load paths (especially at joints).	Structural efficiency as reduced volume, reduced weight, reduced schedule, and/or reduced complexity. /All Missions	TRL 2, In development stage, though some of the technologies exist individually (ARMD)	Demonstration of capabilities with a prototype structure and a to be determined DRM.
i. Integrated Adaptive Success of this technology requires the cooperation of multi-disciplines: structures, dynamics, thermal control, instrumentation.	Ability to make thermal-structural adjustments in space without supporting missions. /Human Space Flight/Habitable Modules	TRL1, Conceptual to immature. Depends upon outcome of supporting technologies that are under development	Advances in testing and data collection, automated technique in data analysis and algorithms for interpretation of results in structural health monitoring.

Figure 1.2: Reproduced from NSA Technology Roadmap TA12.

1.5 Summary of First and Second Workshops

The first workshop (W1) took place on May 19-22, 2014, and the second workshop (W2) took place on February 17-19, 2015.

The goals of the first workshop were to determine a set of reference missions, system capabilities/architectures, and technologies that have the best chance of enabling multifunctional and energy-projecting systems (EPMFS) in future missions. The parameter space considered in the Study is shown in Figure 1.3.

Based on the feedback received at the end of the first workshop, the goals of the second workshop were to report the results of a prototypical technical trade study for microclimate control involving

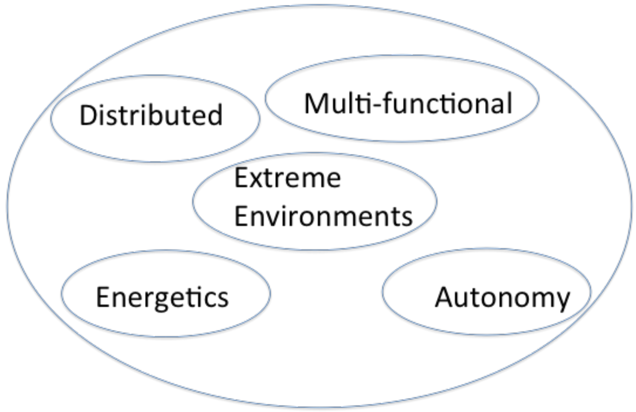


Figure 1.3: Technology parameter space discussed in the Study.

exploration of alternate architectures and the identification of technology needs in the following technical areas:

- Multifunctional systems
- Energy harvesting, conversion, distribution
- Distributed system architectures

Mission applicability was addressed in terms of relevance to extreme environments and enabling aspects of NASA mission classes. Four planetary environments were considered in the Study:

- Titan
- Craters/caves on Moon
- Craters/caves on Mars
- Venus

The mapping between the capabilities and the planetary environments is outlined in Table 1.1.

Six promising high-level technologies were identified that could provide those capabilities and enable new planetary science missions to those environments. These are illustrated in Figure 1.4 and described in Table 1.2 and are:

- **Reflecting to PV:** Reflecting solar energy to a small photovoltaic (PV) array
- **Converting and Beaming:** Converting solar energy via PV to another wavelength (microwave, laser) and beaming that energy (either orbiting or ground-based)

Table 1.1: Mapping Between Mission Capabilities and Planetary Environments

Capabilities	Lunar South Pole	Venus	Asteroid	Titan	Mars Caves	Mercury Caves	Human Exploration
In Situ Energy Generation	✓	✓	✓	✓			✓
Energy Storage	✓	✓	✓	✓			✓
Energy Distribution	✓	✓	✓	✓	✓	✓	✓
Long-Term Survivability		✓	✓	✓			
Leverage Multiple Assets	✓	✓	✓	✓	✓	✓	✓
Flexible Energy Infrastructure	✓		✓		✓	✓	
Ensure Line-of-Sight	✓				✓	✓	
Energy Harvesting		✓	✓	✓	✓	✓	

- **Concentrating and Converting:** Concentrating solar energy locally and converting it directly to another wavelength (e.g., solar-pumped laser)
- **Areal Harvesting:** Areal "power plants" (kites, balloons) that harvest energy from atmosphere and transmits energy to lander stations (cable, beaming)
- **Windmills:** Ground-based windmills as electrical generators
- **Deployed Array:** Large-area deployed array for a stationary lander

Twelve different low-level technologies were deemed to be relevant to realize the above capabilities. These are shown in Table 1.3, and are:

- Large, low-mass, flexible PV arrays
- Large, low-mass, reflective surfaces
- Shape-changing membranes
- Energy conversion systems
- Low-load deployable structures

Table 1.2: Identified High-Level Technologies

High-Level Technology	Titan	Craters & Caves (Moon)	Craters & Caves (Mars)	Venus	Assessment
Reflecting to PV	✓	✓	✓		Works well to provide low power to a wide area, such as a swarm of low-power rovers or a ground base station. Not as suited for Titan or Venus due to low efficiency and losses through atmosphere.
Converting & Beaming	✓	✓	✓		More efficient conversion can be optimized for the desired wavelength. Needs receiver hardware. Highly directional with minimal collateral damage.
Concentrating & Converting	✓	✓	✓	✓?	Avoids inefficiency of PV conversion. Needs energy conversion technology development. Same advantages as above.
Areal Harvesting	✓		✓	✓	Could use wind or thermal variations. Poses difficult steering problems for beaming. Need to assess the value of this architecture.
Windmills	✓		✓	✓?	
Deployed Array	✓			✓	Roll out thin film arrays to provide low power.

- Load-bearing/constructed structures
- Steering, pointing, and targeting
- Multifunctional communication (embedded antennas in structure, or dual-use beam)
- Placement of distributed assets
- Extreme temperature materials (high and low), including PV cell
- Robust, light-weight cables
- Tailored PV cells for optimum efficiency (high intensity, or frequency)

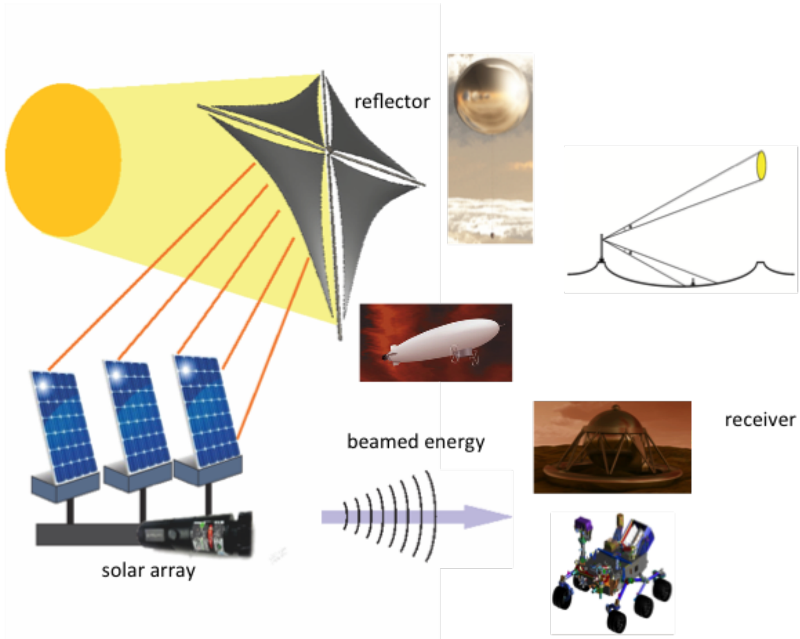


Figure 1.4: Mission concepts discussed in the Study.

Hardware requirements to implement key components of the technologies discussed above (solar cell arrays; actuation, sensing and control; sensors; reflectors for multi-hop; active support structures; and manufacturability) are summarized in Table 1.4.

1.5.1 Identified Mission Capabilities

The list of missions outlined above demonstrates the multitude of challenges presented by future surface missions. Challenges general to virtually all of the surface missions include:

- Limited bandwidth and high-latency communications preclude real-time teleoperation (except to the Moon); thus, requiring a high degree of autonomy and reliability.

- Harsh environments lead to rapid degradation of components/systems and significant aging during longer missions. Achieving the required robustness and fault-tolerance in a cost-effective manner is a challenge of growing importance.

- The limited capability of available radiation-tolerant, flight-qualified processors constrains onboard processing even while avionic and software systems continue to grow in complexity. Currently, the performance gap between standard commercial processors, where the trend is toward greater parallelism, and flight processors remains large. Obtaining the levels of robustness and reliability required for space applications in the face of increasing cost constraints remains an open problem.

Table 1.3: Identified Low-Level Technologies

	Reflecting to PV	Converting & Beaming	Concentrating & Converting	Areal Harvesting	Windmills	Deployed Array
Large, low-mass, flexible PV arrays	✓	✓				✓
Large, low-mass, reflective surfaces	✓		✓			
Shape-changing membranes	✓?		✓	✓	✓	
Energy conversion systems		✓	✓	✓	✓	
Low-load deployable structures	✓	✓	✓	✓		
Load-bearing/ constructed structures	✓	✓	?	?	✓	
Steering, pointing, & targeting	✓	✓	✓	✓		
Multifunctional communication	✓	?	✓	✓		✓
Placement of distributed assets	✓	✓	✓			
Extreme temperature materials	?		✓	✓	✓	✓
Robust, light-weight cables				✓	✓	
Tailored PV cells for optimum efficiency	✓			✓		✓

- Perhaps the single greatest determining feature of surface missions is the need to operate in a complex and only partially understood environment. We should point out that natural environments on planets are not always analogous to Earth. For example, comet surfaces, cryo-lakes, thermal extremes in shadows, etc., can require novel system designs and autonomy algorithms tailored for these new environments. Many of the future missions detailed above involve levels of interaction with the environment (terrain and soil, atmosphere, and lakes) far beyond those previously demonstrated. There is a need for improved environmental models as well as for planning and control algorithms that are robust to significant uncertainties to better address the challenges of steep slopes,

Table 1.4: Hardware Requirements

Solar Cell Array	• Photovoltaic cells: high efficiency • Low mass density • Waste heat recovery
Actuation, Sensing, & Control	• Correctibility: high actuation strain & high sensitivity • Low power needs (set & hold capability) • Low mass density • Survivability & robustness (e.g., on Venus)
Sensors	• Temperature • Wind speed • Pressure • Microwave power sensor • Pointing • Structural & system health sensors (SHM)
Reflectors for Multi-Hop	• High surface quality (wavelength considerations) • Low thermal expansion coefficient • Thermal conductivity • Heat capacity • Foldability (large, reversible deformation) • Survivability • Mechanical robustness
Active Support Structure	• High actuation efficiency (strain vs. power) • Thermal robustness • Mechanical robustness • Damping capacity • Foldability (large, reversible deformations) • Mobility
Manufacturability	• In situ space fabrication (e.g., 3D printing) vs. on-ground fabrication • Robotic assembly • Deployability

operations in low gravity, or for aerial vehicles operating in changing and poorly understood winds.

1.5.2 Identified System-Level Technologies

Key technologies that will enable the capabilities outlined above include:

Table 1.5: Computational Classes

	Low Risk	Medium Risk	High Risk
Class 1: Nominal	Next Generation Signal Processor (NGSP) (dual/quad core) / Use in small array	"Cloud" computation framework (100 servers), managed by NGSP	40k-core / neuromorphic architectures with tandem cloud / NGSP backbone
Class 2: Expect controlled environment for operation, but storage at extreme temperatures	Rad 750 or NGSP, with special packaging (hot environment may not work)	Rad 750 or commercial core in rad-hard HiTemp SOI technology (150°C)	Rad 750 or commercial (low) in exotic tech (hi) (SiC, vacuum tube, MEMS)
Class 3: Operate at temperature in environment	(hot) none / (cold) rad6000 (verify operate at 90k)	(hot) none / (cold) lower-power core (verify at 90k)	(hot) 16-bit in exotic tech / (cold) 32-bit ultra-low power (ULP) CMOS
Class 4: Operate at temperature in environment	(hot) simple FSM or analog / (cold) 8-bit CPU	(hot) 200-2k-gate FSM / (cold) low-power CPU	(hot) 8-bit CPU / (cold) ULP 8-bit

- Deployable
- Multifunctional
- Reconfigurable
- Multi-hop
- Dual-hybrid
- Tethered distribution

Table 1.6: Technologies that Impact KISS Study Capabilities

	Deployable	Multifunctic	Reconfigura	Multi-Hop	Dual Hybrid	Tethered Distribution
In Situ Energy Generation						
Energy Storage					✓	
Energy Distribution						✓
Long-Term Survivability		✓	✓		✓	✓
Leverage Multiple Assets	✓			✓		✓
Flexible Energy Infrastructure				✓	✓	✓
Ensure Line-of-Sight	✓			✓		
Energy Harvesting					✓	

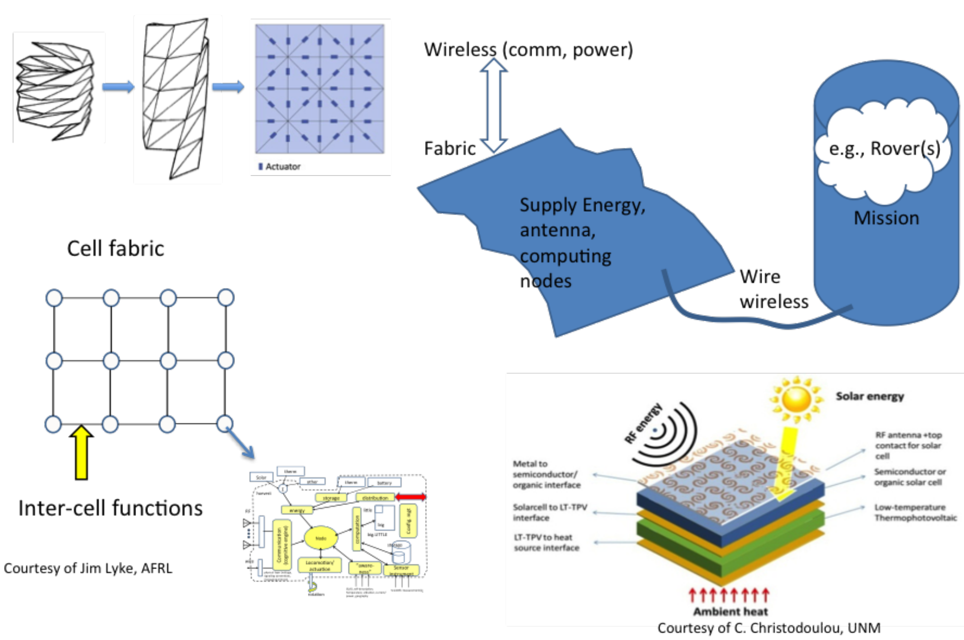
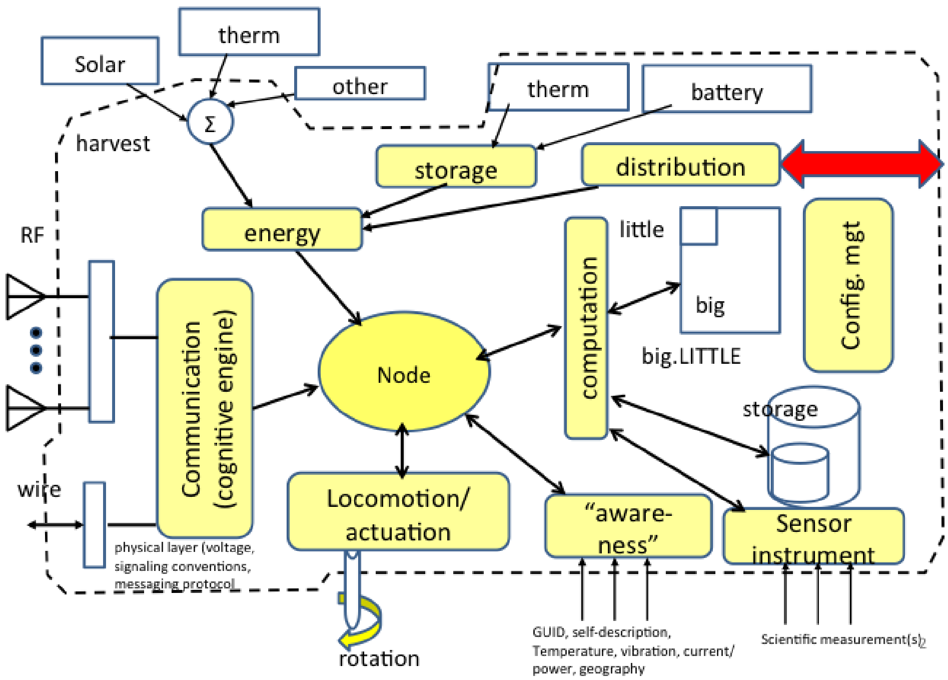


Figure 1.5: Technology areas to be explored for deployable multifunctional systems.



Courtesy of Jim Lyke, AFRL

Figure 1.6: Node architecture.

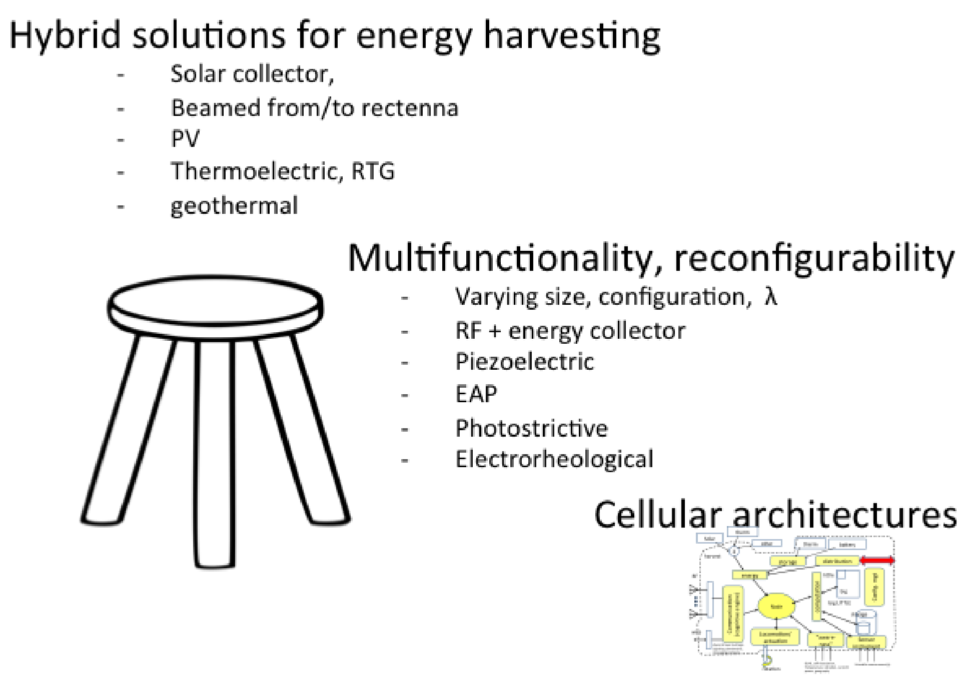


Figure 1.7: Three technology pillars that were identified in the Study.

2. Technologies Explored in the Study

2.1 Multifunctional Deployable Systems

Summary:[1] Planetary exploration by means of autonomous rovers is limited by various factors primarily centered on the size and power generation capabilities of the rover itself. Installing a radioisotope thermoelectric generator (RTG) on a rover would enable it to sustain itself for the duration of the mission, thereby removing the dependence on solar energy. Due to the cost and complexity of the RTG, its mission design, mobility, and maneuverability would be greatly compromised. As a result, a compact and agile design for the rover, required for exploration of intricate and scientifically valuable locations like caves and crevasses would be limited with an RTG. This section looks at the feasibility and deployment of a novel technique based on flexible electronic multifunctional systems (MFS) for modular and agile rovers to enable exploration of previously inaccessible terrain. The entire MFS is proposed to be built from a single, thin sheet; a flexible substrate of Mylar, Steel or Plastics (PEN, PI). This substrate would be manufactured as a thin ($\approx 100\ \mu m$) and light flexible layer, survivable to extreme environments. Along its large surface, this entire sheet could be partitioned into modular 'tiles' to serve different programmable purposes. This section looks into the use of the flexible MFS for deploying large solar panels and also solar reflectors on the same plane so as to serve as a means of power generation and also directing the solar radiation onto a target body (ex. a rover) which is not receiving sufficient solar radiation. Flexible MFS would remain in a tightly-folded stowed configuration and would self-unfold to take the shape/function needed by the mission target, and then again transform its shape as needed. This section systematically examines the system requirements in order to achieve this folding and unfolding actuation. The system level study also includes an analysis of the possible configurations for development of flexible electronics MFS, based on the current research and proven space technology. We explore the use of flexible electronics as a basis for advancing the applications of space robotic exploration. Implementation of flexible electronic systems on rovers will provide improved mobility, modularity and maneuverability capabilities.

2.1.1 System Overview And Feasibility

MFS can be used in conjunction with rover exploration, projecting a favorable micro-environment into cold and dark areas. These applications are driven by the need for a thin, low mass, large-area structure (e.g., polymer-based), which could not be implemented using conventional engineering materials such as metals and alloys. In each case, there is also the need to integrate sensing and control electronics within the structure. The flexible electronic deployment and retraction sub-system would be concerned with the following aspects of the system-level design in order to better establish the feasibility and implementation of this technology:

- Flexible Electronic Material
  - Substrate
  - Backplane electronics
  - Front plane electronics
  - Encapsulation
- Actuators
  - Type
  - Size
  - Power
  - Control
  - Repeatability
- Packaging and deployment sequence
- Thermal requirements

Figure 2.1 shows a simple outline of the components involved in the design of flexible electronics-based MFS. The most crucial element is the flexible substrate on which the Thin Film Transistors (TFTs) would be embedded (or grown) and the actuators and auxiliary electronics mounted. This would dictate the minimum bending/folding capabilities of the MFS without compromising the functionality of the embedded devices. The mounting scheme for the devices, which are to be externally mounted onto the substrate, would also influence the folding and deployment capabilities. This aspect will be examined further in the interconnects and contacts section. The control algorithm would determine the crease pattern, which needs to be made on the surface of the substrate. It would also determine the actuation sequence for the Shape Memory Alloys

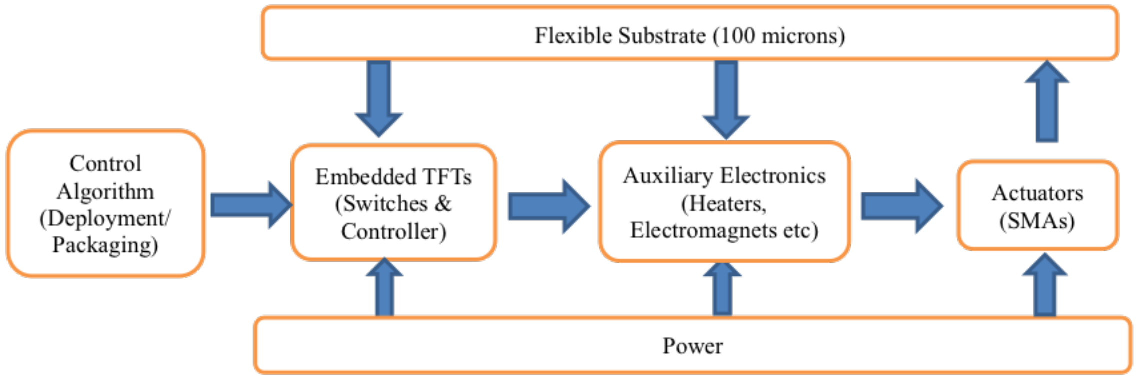


Figure 2.1: Simple outline of the components involved in the design of flexible electronics-based MFS.

(SMAs) present on the substrate. The control algorithm would then be chosen to minimize the number of overlapping folds and the number of actuators required to achieve complete deployment.

Options For Thin Layer Fabrication

To provide the desired suite of functionality, the MFS surface may need to be quite large; even so, if thin, it could be packed into a small volume during flight. Assuming the mission allows for a 1 m^3 packed MFS, a surface of 100 microns, can unfold to an area of 10,000 m^2, (i.e., a square 100 meters on a side). Made of a gossamer-thin, flexible multi-layer sheet, they may have one side covered with solar cells, and the other side with a highly reflective coating, while inner layers compute, self-actuate to change shape, store energy in batteries, and embed a spider-web antenna. All of these subsystem functions have been individually demonstrated on thin flexible layers of tens of microns (some shown in Figure 2.2): power from solar arrays,[2] avionics circuits,[3]

[2] Sasaki, T., Suzuki, H., Inagaki, M., Ikeda, K., Shimomura, K., Takahasi, M., ... & Yamaguchi, M. (2012). Real-Time Structural Analysis of Compositionally Graded InGaAs/GaAs (0 0 1) Layers. Photovoltaics, IEEE Journal of, 2(1), 35-40; Lo, S. Y., Wuu, D. S., Chang, C. H., Wang, C. C., Lien, S. Y., & Horng, R. H. (2011). Fabrication of flexible amorphous-Si thin-film solar cells on a parylene template using a direct separation process. Electron Devices, IEEE Transactions on, 58(5), 1433-1439.)

[3] Pornsin-Sirirak, T. N., Tai, Y. C., Nassef, H., & Ho, C. M. (2001, January). Flexible parylene actuator for micro adaptive flow control. In Micro Electro Mechanical Systems, 2001. MEMS 2001. The 14th IEEE International Conference on (pp. 511-514). IEEE.

controls,[4] sensing,[5] shape-memory alloy actuation,[6] communication circuits,[7] and antennas.[8] The study will include system integration of the sub-systems by same-layer integration options, as demonstrated by Epidermal electronics[9] and by multi-layer stacking.[10]

Figure 2.2: Sub-systems built on flexible layers: electronics, actuation, antenna, and solar cells; epidermal electronics (rightmost) integrates several of them in the same thin, peelable layer.

Options For Fine-Grain Cellular Architectures

The MFS fabric is likely to have a cellular structure, each cell including multiple sub-system functions; cell communication is local. Distributed information processing, communications, and control would be achieved by groups of cells. Both homogeneous (one cell type) and heterogenerous designs (multiple cell types with various primary subsystem roles), will be explored. The cells will have flexibility at their perimeter, forming a tessellated structure, which can change shape by actuation of elastomer joints at cell borders. Triggering the proper actuator groups in sequence produces a shape. This may follow an origami-type folding to shape a diversity of 3D shapes. Work in these areas for specific subsystems has been done under programmable matter[11]

[4]Ouyang, P. R., Tjiptoprodjo, R. C., Zhang, W. J., & Yang, G. S. (2008). Micro-motion devices technology: The state of arts review. The International Journal of Advanced Manufacturing Technology, 38(5-6), 463-478.

[5]Jiang, F., Tai, Y. C., Walsh, K., Tsao, T., Lee, G. B., & Ho, C. M. (1997, January). A flexible MEMS technology and its first application to shear stress sensor skin. In Micro Electro Mechanical Systems, 1997. MEMS'97, Proceedings, IEEE., Tenth Annual International Workshop on (pp. 465-470). IEEE.

[6]Torres-Jara, E., Gilpin, K., Karges, J., Wood, R. J., & Rus, D. (2010). Compliant modular shape memory alloy actuators. Robotics & Automation Magazine, IEEE, 17(4), 78-87.

[7]Ahn, J. H., Kim, H. S., Lee, K. J., Jeon, S., Kang, S. J., Sun, Y., ... & Rogers, J. A. (2006). Heterogeneous three-dimensional electronics by use of printed semiconductor nanomaterials. science, 314(5806), 1754-1757.; Christiaens, W., Bosman, E., & Vanfleteren, J. (2010). UTCP: A novel polyimide-based ultra-thin chip packaging technology. Components and Packaging Technologies, IEEE Transactions on, 33(4), 754-760.

[8]Furuya, H., Ning, G. U. A. N., & Himeno, K. (2007). Characteristics of a deformed antenna made of flexible printed circuit. IEICE transactions on communications, 90(9), 2225-2229; Novel Technologies for Elastic Microsystems: Development, Characterization and Applications 2011, http://www.cmst.be/publi/docfb2.pdf

[9]Kim, D. H., Lu, N., Ma, R., Kim, Y. S., Kim, R. H., Wang, S., ... & Rogers, J. A. (2011). Epidermal electronics. Science, 333(6044), 838-843.

[10]3D-WLP: http://www.imec.be/ScientificReport/SR2008/HTML/1224991.html

[11]Towards a Programmable Material, MIT, (2000): http://groups.csail.mit.edu/mac/projects/amorphous/Progmat/thesis/

and origami robots projects.[12] An example of the use of origami in producing a large-scale foldable structure is the Eyeglass Telescope built by Los Alamos National Laboratory.[13] Some of these concepts are shown in Figure 2.3.

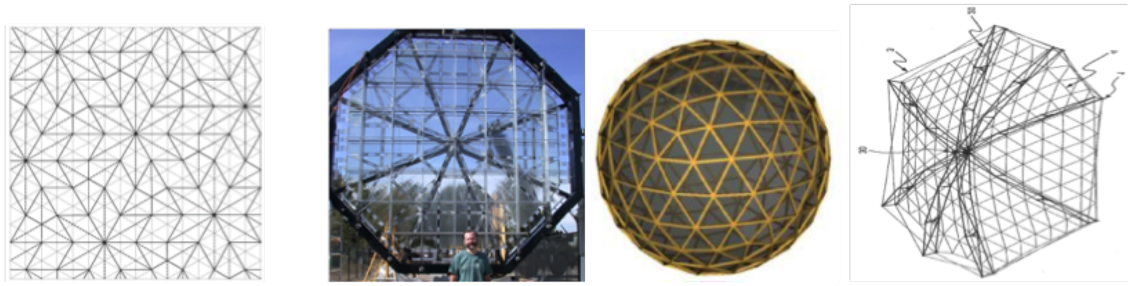


Figure 2.3: (a) Cellular architecture of T-fabric, allows origami-like folding designs; (b) LANL Eyeglass telescope used origami-folding for a large structure (c) MFS as a sphere, (d) Japanese design for a deployable antenna.[14]

2.1.2 Flexible Electronics-Based MFS Design Configuration

Table 2.1 shows two feasible configurations for flexible MFS. An analysis on the reasoning behind the selection of these components/techniques follows.

Table 2.1: Two Feasible Configurations for Flexible MFS

Property	Configuration 1	Configuration 2
Substrate	4 cm	1.5 mm
Bending Radius	Steel	Mylar (PET)
Back Plane Electronics	a:Si-H (amorphous)	nc:Si-H (nano crystalline)
Actuators	Ni-Ti	Ni-Ti
Auxiliary Electronics	Heater Coil, Electromagnets	Bidirectional SMA, Heater Coil
Deployment Technique	Box-Pleated Folding Configuration	Folding Cylinder

Flexible Electronics Material Selection

Based on the application of this technology it is required that the material selected be bendable, rollable and elastically stretchable. The following equation is a good approximation for the strain

[12] Onal, C. D., Wood, R. J., & Rus, D. (2013). An origami-inspired approach to worm robots. Mechatronics, IEEE/ASME Transactions on, 18(2), 430-438.
[13] http://sketchup.google.com/3dwarehouse/details?mid=58a3c639cec2ae758fc5761c4e5e82ed&ct=mdrm
[14] Deployable Antenna http://www.faqs.org/patents/app/20120193498

developed in the material during bending: $\varepsilon = d/2r$, where, ε is the strain, d is the thickness, and r is the bending radius. Depending on the material selected, the strain limit can be determined. For example, for a 100-micron sheet of a-Si:H (hydrogenated amorphous silicon), strains of 0.1-1% can be tolerated without affecting the electrical performance of the device. In order to further improve the performance and bending characteristics of the device, the transistors are grown on the neutral plane to minimize the strain they experience by during bending. Net-like configurations can be employed with the electronic transistors placed on the ribs of the net in order to improve the elastic characteristics of the device.

Substrate Material Requirements

The substrate requirements would be obtained as follows:

- T_g (Glass Transition temperature) must be compatible with the maximum fabrication temperature, i.e., $|\Delta CTE \cdot \Delta T| \leq$ (0.1- 0.3)%, where, ΔT is the temperature during extrusion and ΔCTE is the difference in the coefficient of thermal expansion.
- High thermal conductivity
- High Young's modulus
- Type (based on application):
  - Conductive substrate is usually preferred as it serves as a common node.
  - Insulating substrate minimizes the coupling capacitance.
  - Magnetic substrate is favorable in mounting applications.

The properties for substrates for flexible backplanes are listed in Table 2.2.[15]

Table 2.2: Some Properties for Substrates for Flexible Backplanes

Property	Unit	Glass (1737)	Plastics (PEN,PI)	Stainless Steel 430
Thickness	microns	100	100	100
Weight	g/m^2	250	120	800
CTE	ppm/°C	4	16	10
Elastic Modulus	GPa	70	5	500
Max. Process Temperature	°C	600	180,300	1,000
Safe Bending Radius	cm	40	4	4

[15] Cheng, I. C., & Wagner, S. (2009). Overview of flexible electronics technology. In Flexible Electronics (pp. 1–28). Springer US.

Stainless steel possesses superior mechanical properties that support its selection as a suitable substrate material. For the purpose of insulation it is required that the steel be covered by a layer of either SiN or SiO_2. Mylar is also a possible choice for substrate material. Tellurium thin-film triodes (TFT) have been shown to grow on Mylar, having a bending radius of 1.5mm.[16] Depending on the thermal requirements and the final mass constraint for the design, the choice of the substrate material can be made between polyethylene terephthalate (PET), Steel and polyimide (PI).

Backplane Electronics

While many promising results have been reported with organic semiconductors, the performance and lifetime of such devices suffer from low carrier mobility and poor chemical stability, which hinders their use for most electronic applications. On the other hand, inorganic semiconductors provide superior carrier mobility and chemical stability. However, the great challenge lies in integrating brittle inorganic semiconductors on flexible substrates while preserving the structural and electrical properties. The transfer-and-bond approach and direct fabrication methods are two available approaches to bond the inorganic TFTs to the substrates listed earlier. The direct fabrication method relies on polycrystalline or amorphous semiconductors because these can be grown on foreign substrates.

The requirements for backplane electronics material are:

- Rugged
- Rollable
- Bendable
- Capable of complementary metal-oxide semiconductor (CMOS) operation
- Examples are:
  - Silicon TFT: These materials benefit from well-established technology for manufacturing and processing.
  - Hydrogenated Amorphous Si TFT (a-Si:H); Substrate Temperature: 250-350°C; used for developing n-channel metal-oxide-semiconductor field-effect transistors (MOSFET); developing technique: plasma-enhanced chemical vapor deposition (PECVD)
  - Nanocrystalline Silicon (nc-Si:H); Substrate Temperature: 250-3500 C; CMOS capabilities, Developing technique: PECVD.

[16]Wong, W. S., & Salleo, A. (Eds.). (2009). Flexible electronics: materials and applications (Vol. 11). Springer Science & Business Media.

Interconnects and Contacts

The critical crack strain for the connectors is inversely proportional to the square root of the substrate thickness. To develop stretchable and bendable interconnects, the following techniques were adopted: 1) Combining elastomers with conductive polymers; 2) Combining elastomers with metal particles; and 3) Metal film encased in elastomers. Studies conducted by Wagner et al.[17] have shown that compressive stress in the gold film induces spontaneous wrinkling, which can shrink the net length of the thin-film conductors by several tenths of a percent; this strain can be used to raise the stretchability of the gold films above their fracture strain of, typically, 1%. Thin metal films—e.g., a 100-nm-thick layer of gold on top of a 5-nm-thick adhesion interlayer of chromium—were deposited in one run by successive electron beam evaporation onto elastomeric substrates of polydimethylsiloxane (PDMS) held at room temperature. It was experimentally determined that the stripes can retain electrical continuity when stretched by as much as 22%.

2.1.3 Actuators

Selection of the actuators is dictated by the following constraints:

- Power requirement for deploying and folding
- Displacement achieved
- Actuation force (torque)
- Size
- Compatible with TFTs

Based on the constraints listed above, the following actuators have been considered:

- Electroactive Polymers (EAP):
  - Principle: The EAP actuator can be modeled as a capacitance with compliant electrodes, where the insulator is the dielectric polymer, as shown in Figure 2.4.[18] When an electric field is applied across the polymer, an electrostatic pressure, also known as the Maxwell stress, rises between the charged electrodes bringing them closer together, and spreading them out. Due to this effect, the film expands sideways when squeezed in thickness.
  - Power Requirements: EAP can undergo large actuation strains of up to 200% under

[17] Lacour, S. P., Wagner, S., Huang, Z., & Suo, Z. (2003) Stretchable gold conductors on elastomeric substrates. Appl Phys Lett 82:2404–2406

[18] Lacour, S. P., Prahlad, H., Pelrine, R., & Wagner, S. (2004). Mechatronic system of dielectric elastomer actuators addressed by thin film photoconductors on plastic. Sensors and Actuators A: Physical, 111(2), 288-292.

electrical stimulation of typically 100-150 V/m.

– Drawbacks: Actuation Type: Linear; A lever arm mechanism or coupling would need to be developed to achieve folding of the flexible substrates. Displacement: ∼30-45 microns. EAP is compatible but not ideally suited for this application.

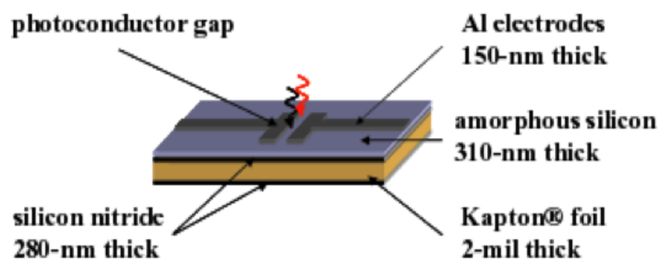


Figure 2.4: The EAP actuator can be modeled as a capacitance with compliant electrodes, where the insulator is the dielectric polymer.[19]

- Actuator Based on Polypyrrole:
  - Principle: The conjugated polymer polypyrrole undergoes a volume change of several percent when its oxidation state is changed electrochemically. Illustration shown in Figure 2.5.[20]
  - Actuation Displacement: 0-180°
  - Actuation Voltage: 0 to -1 V
  - Energy: Mass ratio – 40 mJ/g
  - Power Density: ∼7.5 mW/g
  - Drawbacks: The polymer must be in contact with an electrolyte that can serve as a source/sink of ions in order for this reaction to occur; since an aqueous solution of sodium dodecylbenzene-sulfonate (NaDBS) is used as an electrolyte, this design would not be suitable for space use.
- Actuators based on Shape Memory Alloy:
  - The most common SMA is Ni-Ti (Nitinol) alloy used for its ductility and fatigue and corrosion resistance (Figure 2.6).

[19] Ibid.

[20] Smela, E. (1999). A microfabricated movable electrochromic "pixel" based on polypyrrole. Advanced Materials, 11(16), 1343-1345.

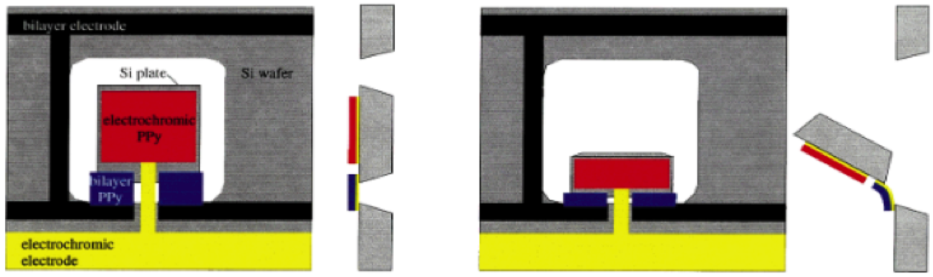


Figure 2.5: Actuator Based on polypyrrole.[21]

- Principle: Heating past the alloy's transition temperature results in a change in the crystal structure, in which the martensite composition of the alloy turns into austenite crystals. This shift is called 'twinning' and a shape change is associated with this twinning. In order to concentrate the heating near the axis of rotation, a heating coil (Ni-Cr coil) is employed. As the actuator is no longer part of the circuit, only two ends need to be fixed to the substrate at opposite sides of the actuated joint. The elimination of electrodes simplifies the shape and enables further miniaturization. On the basis of the tests conducted by Paik et al.,[22] the values for the actuators are listed below.
- Actuation type: Torsional actuation (0-180°).
- Dimensions: 12mm x 7mm x 100 microns (thickness)
- Minimum Bend radius: 500 microns
- Power Requirements: 180° actuation, 0.19 A at 13 V (Heating coil)
- Power Consumption: 3.6W
- Mass: 68 $\cdot 10^{-6}$ kg
- Torque: 0.0045 N m
- Drawbacks: The SMA tends to fatigue at 5% strain after 100 cycles.
- Given the size of the actuator and the range of motion it provides, Ni-Ti based SMA can be considered to be a preferred choice of actuator for the purpose of deploying and folding of flexible electronics-based MFS. Two SMA actuators can be used with their rotation aligned opposite to each other to obtain a bi-directional actuation.

[21] Ibid.

[22] Paik, J. K., Hawkes, E., & Wood, R. J. (2010). A novel low-profile shape memory alloy torsional actuator. Smart Materials and Structures, 19(12), 125014.

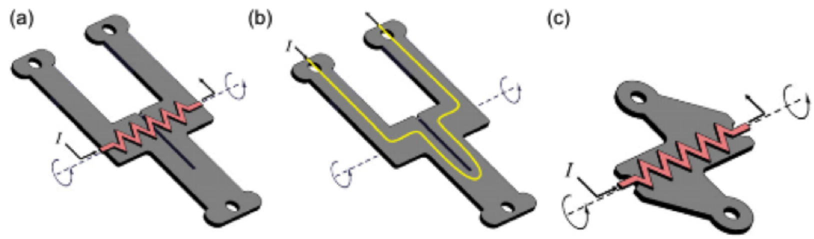


Figure 2.6: Actuators based on shape-memory alloy.[23]

2.1.4 Folding And Deployment Techniques

For the deployment of flexible MFS, it is critical to estimate the most efficient pattern of creases on the surface of the plane that needs to be folded. The pattern of the crease selected and the order in which the substrate is folded will be discussed further in this section. On the basis of the research conducted by Demanie et al.[24] it was shown that an n x n box-pleated crease pattern is capable of reaching any folded state without the material penetrating itself. Figure 2.7 shows an 8x8 box-pleated crease pattern. This pattern can be considered suitable for our application since it provides the capability of varying the final deployed configuration of the MFS (reflector) and modifying it as the environment may dictate.

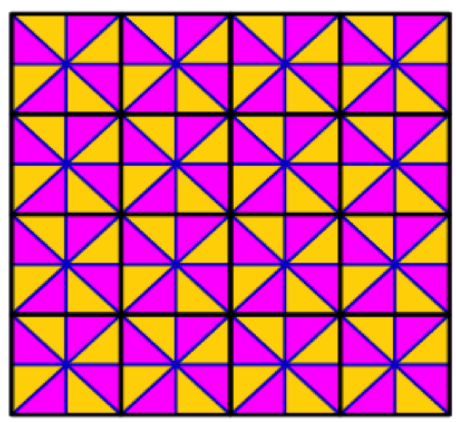


Figure 2.7: An 8x8 box-pleated crease pattern.

In order to achieve a fold along the crease, actuators are required to be placed at the diagonals and the edges of the squares as shown in Figure 2.8 for a 4x4 box-pleated crease pattern. Similar experiments have been conducted at the Distributed Systems Laboratory at MIT to explore the capabilities of folding systems.[25]

[23] Ibid.

[24] Benbernou, N., Demaine, E. D., Demaine, M. L., & Ovadya, A. (2009). A universal crease pattern for folding orthogonal shapes. arXiv preprint arXiv:0909.5388.

[25] An, B., & Rus, D. (2014). Designing and programming self-folding sheets. Robotics and Autonomous Systems, 62(7), 976-1001.

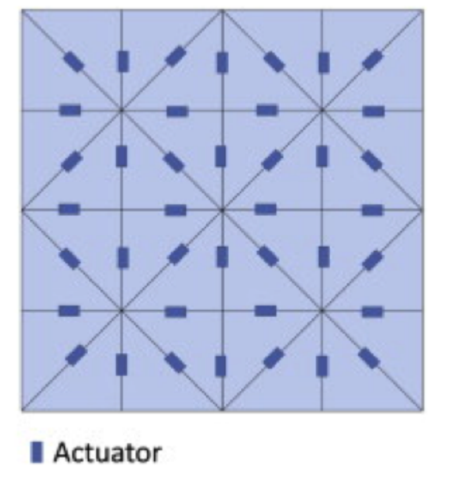


Figure 2.8: An actuated 4x4 box-pleated crease pattern.

The smallest folded configuration formed from the pattern shown above would have a surface area equal to the area of the isosceles triangle into which the square has been divided. The strains in the folded state would be comparatively high and are required to be examined in detail to judge the feasibility of the folded state.

The folding algorithm design would depend on the following factors:

- Final folded configuration of the plane required.
- Minimization of the strain levels in the creases.
- Minimization of the number of actuators to be used.

A representative algorithm for a 4x4 plane to a unit isosceles triangle is shown in Figure 2.9.

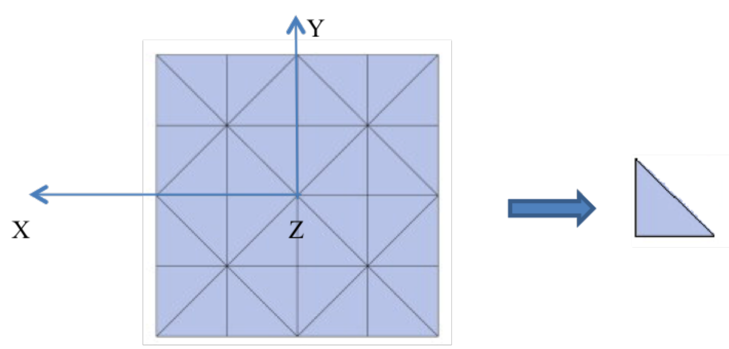


Figure 2.9: Folding to an isosceles triangle.

In order to keep a fixed coordinate reference for the plane, the folding operation is performed symmetrically about the z-axis (into the paper) passing through the center of the plane. The reduction in area obtained for a 4x4 box-pleated design is 96.7%. This is done ignoring the minimum bending radius to be considered for the substrate and the devices mounted on it. We also assume that the creases fold perfectly to 180°, which would not be the case in the actual scenario. The folding is done sequentially; that is, the 4x4 matrix is first reduced to a 2x2, which is then finally folded into an isosceles triangle. The steps involved in the folding operation are described below with the help of Figure 2.10.

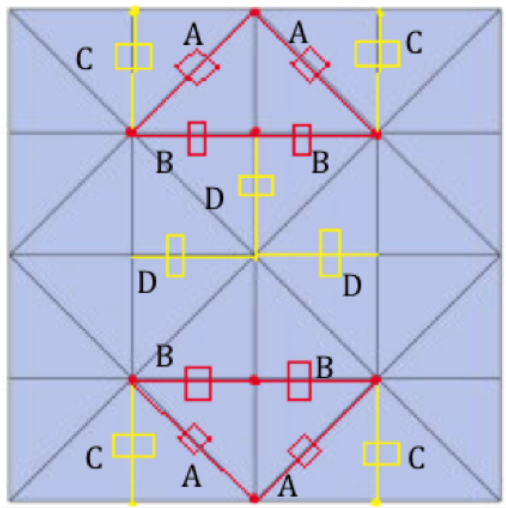


Figure 2.10: Sequence of folding operations to a obtain triangle.

The red and yellow creases indicated folds in opposite directions to each other. The number of actuators required is 15, and the number of folds is 10. Actuating the SMA actuators A and B results into the formation of 2x2 box-pleated plane. Actuator C and D will finally result in the formation of a unit isosceles triangle.

2.1.5 Deployment And Packaging Mechanism

A power-efficient and realizable method for deployment of the flexible electronics-based reflector/ array is necessary. We have shortlisted SMAs as a possible means of achieving the maximum actuation in the most power-efficient manner. Incorporating the use of SMAs with electromagnets possesses the capability to be an efficient deployment and packaging technique. This technique involves the use of 1 electromagnet in combination with 1 (or 2 for better efficiency) SMA actuator. Figure 2.11 shows a flexible electronic substrate with incorporated SMAs and electromagnets fabricated at the Distributed Robotics Laboratory at MIT.[26]

[26]Image courtesy of Distributed Robotics Laboratory at MIT.

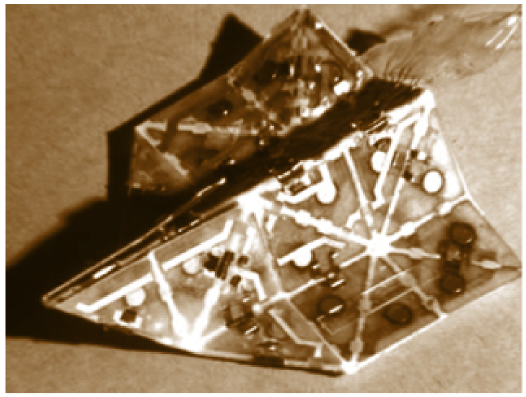


Figure 2.11: Flexible electronic substrate with incorporated SMAs and electromagnets fabricated at the Distributed Robotics Laboratory at MIT.[27]

In Figure 2.11, the magnets are used to hold the flexible MFS in the stowed configuration. The polarity of the magnets is reversed to allow the MFS to deploy. The "springiness" possessed by the SMA present at the creases helps to achieve a fully deployed state. The use of 2 SMAs with their axis of rotation opposite to each other can improve the mechanical efficiency of the system and also provide a shorter deployment time. Apart from embedding the electromagnets into the substrate, the solenoid coils can be printed on the flexible electric substrate and used to hold or deploy the MFS. This method insures the weight of the flexible MFS is kept to a minimum. In order the pack the MFS, the SMA is actuated in a predefined sequence which starts to fold the plane along the creases in order to go back to the stowed configuration. Once the plane folds along the creases, it is held together by means of magnets present on the two folded halves, thus reducing the duty cycle of the SMA actuator considerably and improving the overall power efficiency.

Apart from the folding technique discussed above, there are numerous ways to achieve a compact folded structure. The design to be selected will also need to be integrated with the rigid structural components and mechanism accompanying the flexible MFS for the purpose of stability and mobility (rotation of the reflector/array). These methods include tailoring existing technology, which has been proven reliable in similar domains, to fit the requirements for use in the application of flexible MFS. These systems may include solar panel array deployment and deployable parabolic reflector antenna systems.

Large parabolic reflectors have been deployed in space successfully and can provide a strong foundation for establishing similar deployment techniques for flexible electronics-based MFS. Figure 2.12 shows an image of a deployable MEA antenna.[28] The surface area reduction is much less and the requirement for mechanical / structural support systems is much higher in

[27] Ibid.

[28] Guest, S. D. (1994) "Deployable Structure: Concept and Analysis," PhD Dissertation, University of Cambridge.

comparison to the technique described above. This influences the final mass and the MFS's ability to pack compactly into a small volume.

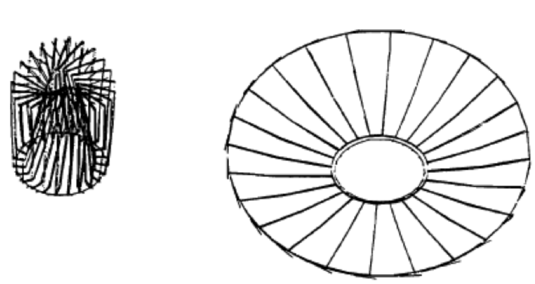


Figure 2.12: Deployable MEA antenna. [29]

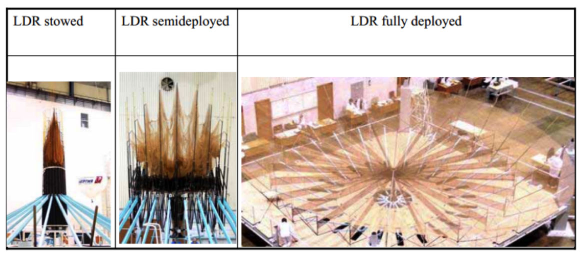


Figure 2.13: ESA Deployable Antenna.[30]

The antenna shown in Figure 2.13 has been developed by the European Space Agency to provide global coverage in applications relating to Earth observations and science applications. The specifications for the antenna are obtained for the ESA LDA design section.[31] The deployed diameter was 12 m and the total mass was 70 kg. The advantages are that the number of folds is reduced considerably. The external skeleton structure simplifies the folding sequence, which can potentially reduce the strain developed in the flexible MFS. The reduction in strain can improve the fatigue life. There are also drawbacks. The current design is a one-time deployment and does not allow the antenna to be repackaged once it has been deployed. This means that a refolding mechanism needs to be added to the device in order to satisfy all requirements for the purpose of flexile MFS for extreme environments. Due to a heavy reliance on the external skeleton structure, the mass of the overall system is high.

Inflatable deployment techniques possess capabilities which can more easily be incorporated into the deployment of flexible MFS in comparison to rigid antenna deployment systems as discussed earlier. By eliminating the need for an exo-skeleton structure to achieve the fully deployed configuration, the overall mass, size, and ability of the system to pack compactly is significantly

[29]Ibid.

[30]Santiago-Prowald, J. (2008, November). Large Deployable Antennas Mechanical Concepts. In Caltech-KISS Large Space Apertures Workshop.

[31]Ibid.

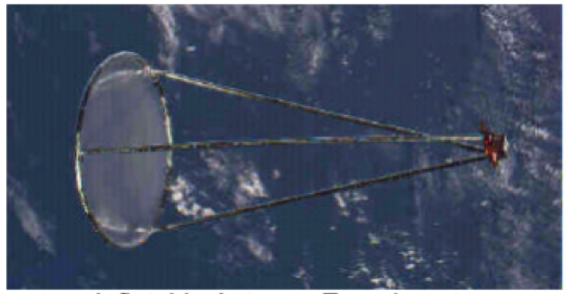


Figure 2.14: Inflatable Antenna Experiment.[32]

reduced. Figure 14 shows the IAE satellite with the fully deployed reflector antenna.[33] The advantages are that no requirement of rigid structure results in reduction of system mass and stowed volume. Proven technology can be tailored to meet the needs of flexible electronic MFS. The drawbacks are the one-time deployment: once the existing system is deployed, it stays in the fully deployed state. A new mechanism would have to be introduced to deflate the inflated structure. The air would have to be stored in tanks available on-board. Depending on the size of the MFS, the size of the tanks would be decided. This would add to the overall volume requirements for the system. Loss in air pressure can be a single point of failure and can also induce instability into the system.

Flexible Electronics Based Folding Cylinder Deployment Technique

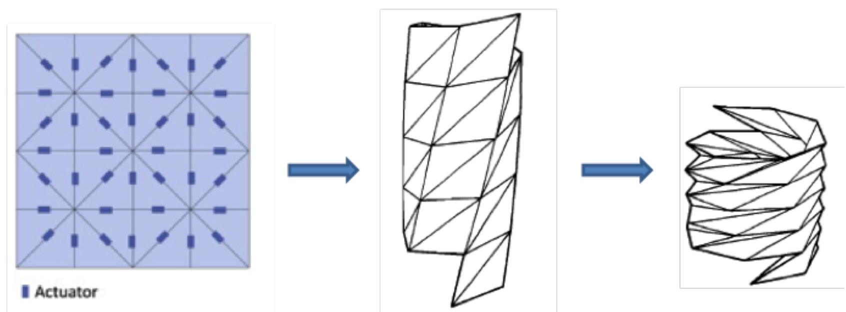
This technique is being analyzed solely for the purpose of achieving an efficient deployment for a flexible electronic based MFS for extreme environments. This technique tries to incorporate existing technology described above with novel features of flexible electronics embedded with SMA actuators in order to achieve an efficient deployment and folding scheme utilizing the minimum resources. Although the reduction in area achieved between the stowed configuration and the fully deployed state is not as high as discussed in the box-pleated folding technique, the number of folds and the angles at which the plane is folded induces considerably less strain on the flexible MFS, thereby reducing the amount of fatigue it will undergo. The folding cylinder technique eliminates the need for compressed air tanks and minimally relies on an external structural support system for deployment and folding as in the case of inflatable antennas and large deployable antennas, respectively. Figure 2.15 shows the steps involved in achieving a fully deployed state from a flexible electronics-based folded cylinder MFS.[34]

[33] Ibid.

[33] Cadogan, D. P., & Grahne, M. S. (1999, May). Deployment control mechanisms for inflatable space structures. In 33rd Aerospace Mechanisms Conference (Vol. 5, pp. 1-12). May.

[34] Guest (1994)

The flexible substrate embedded with SMA actuators is rolled to form a cylinder. This action can be achieved by utilizing the SMAs present on the substrate itself or by means of an external mechanism. The number of rolls about the center axis will determine the radius of the cylinder. It must be noted that while rolling the plane into a cylinder, the creases must align if the rolls overlap, thereby forming multiple layers. Performing this rolling task will achieve the configuration as shown in Figure 2.15B. Once the cylinder is completed, the compression operation can begin in order to obtain the final stowed configuration of the MFS as shown in fFgure 2.15C. This technique relies on the minimal use of externally mounted structures and compressed air tanks. With respect to a single crease, the folds are not additive; that is, the number of overlapping folds is minimized. The strain produced on the substrate can be controlled by adjusting the diameter of the folding cylinder. In order for the compression operation to work efficiently, the creases in the different layers must align with the corresponding crease in the subsequent layers. This would require a high amount of precision by the SMA actuators.



A B C

Figure 2.15: Steps involved in achieving a fully deployed state from a flexible electronics-based folded cylinder MFS.[35]

2.1.6 MFS System Configurations

Different configurations were examined to determine the most reliable, modular, and cost-effective solution possible for the deployment of flexible electronics-based MFS on rovers for the purpose of exploration of extreme terrain that has been deemed inaccessible due to size and power constraints.

Table 2.3 illustrates the possible configurations of substrate material, backplane plane electronics, actuators, and folding and unpacking techniques based on existing technology and on-going research capable of executing the task of deploying and controlling a flexible MFS. The table is ranked in order of preference, where the rank is assigned based on feasibility, reduction in area achieved, complexity, and cost.

[35] Ibid.

Mylar is selected as the primary choice for the flexible substrate material due to its inherent thermal insulation capability and its ability to withstand extreme temperature variations. Tellurium grown on a 100-µm-thick layer of Mylar can be used to fabricate CMOS components, allowing for controller design within the substrate layer itself. The use of Shape Memory Alloys (SMAs) would be the most efficient means for achieving actuation for the flexible MFS given the power and mass constraints. Solenoid coils can be printed on the substrate layer, which (once activated) would allow the folded substrates to be held together by means of the magnetic field generated by the solenoids. Solenoids can be replaced with embedded electromagnets, which would facilitate stronger attraction/repulsion forces between the folds but would also impose a higher power and mass requirement.

Table 2.3: Possible configurations of substrate material, backplane plane electronics, actuators, and folding and unpacking techniques based on existing technology and on-going research capable of executing the task of deploying and controlling a flexible MFS.

Rank	Substrate	Backplane Electronics	Actuators	Bending Radius	Folding & Deployment	Comments
1.	Mylar	Tellurium	SMA & Printed Solenoids	1.5 mm	Folding Cylinder (Fig. 2.15)	Folding system pending analysis.
2.	Steel	nc-Si:H	SMA & Electromagnets	40 mm	Box-Pleated (Fig. 2.7)	"
3.	Plastics (PEN,PI)	nc-Si:H	Two SMA with opposing folding axes	40 mm	Box-Pleated (Fig. 2.7)	"
4.	Glass	a-Si:H	Polypyrrole-based Actuator (Fig. 2.5)	400 mm	Rolling	"
5.	Steel/Mylar	a-Si:H / nc-Si:H	Spring Hinges / Motors	Discontinuous Not a single sheet	Solar Array	Flight Tested
6.	Mylar / Steel / Plastics	a-Si:H / nc-Si:H	Spring Hinges / Motors	1.5 mm–40 mm	Parabolic Reflectors	Flight Tested
7.	Mylar / Steel / Plastics	a-Si:H / nc-Si:H	Compressed Air	1.5 mm–40 mm	Inflatable Antennae	Flight Tested

Conclusions: This section has surveyed the use of modular multifunctional systems to facilitate the exploration of extreme and previously inaccessible environments. After studying the current available technology and on-going research, it can be determined that the 2D solution (flexible substrate) is easier/cheaper to fabricate, packs more compactly, and ensures a wider range of capabilities compared to the current techniques being employed like RTG, deployable antenna, and solar panel structures. Mylar-based substrate material with Tellurium backplane electronics can be considered as one of the leading prospects in the future analysis of flexible electronics due to its small bending radius and high thermal insulation capabilities. The use of Shape Memory Alloys (SMAs) is determined to be the most efficient and reliable mean of actuation and control of the flexible MFS. Folding and deployment techniques like the box-pleated crease pattern and the folding cylinder have also been considered. For an accurate trade-off between these techniques, a dynamic multi-body model for folding the tiles should be investigated in detail to determine the total work needed to achieve a fully packed state from a fully deployed one. The amount of strain generated due the folding operation in each of these methods would be an effective trade study in order to determine the most efficient folding and deployment technique.

2.2 Cellular Architectures for Multifunctional Energy-Projection Systems

Cellular architectures represent an approach for interpreting the structure and function of systems. Even the most complex systems amount to, at one level, nothing more than a collection of primitive (albeit intelligent and flexible) building blocks that can under some set of principles self-organize to form multifunctional structures. It is especially useful when we wish to express an unbounded number of design variations using a relative small number of building blocks. The term "cellular systems" refers to systems whose construction is divided into periodic sections, such as a string of beads (1-D), tiles (2-D), or blocks. In mathematical abstractions, such as cellular automata,[36] we often think of cellular systems as having an infinite extent. In physically buildable systems, of course, systems are not only finite but may have irregular shapes. It is convenient for example, to think of cellular architectures as tilings, analogous to floor tiles, which can be arranged periodically to cover arbitrary floor plans. The primary difference in the tiles we are interested in is that they can be multifunctional, possessing built-in intelligence, sensing, and many internal subsystems, just as the cells in a biological organisms (though not the same types of subsystems). As in multi-cellular organisms, we are interested in combining many of these smart tiles to form larger structures.

We envision that the cells of the cellular system represent "atomic" units, and that a cellular system is a structure involving one or more of these units. Cellular systems can be pre-built at the factory (so to speak), but it is interesting to consider the idea of self-organizing cellular systems. In this case, the non-assembled cellular building blocks are brought together in the field to form a cellular system. Nature gives us many interesting examples, such the formation of a virus capsid from a set of protein building blocks, as suggested in Figure 2.16.

[36] Wolfram, S. (1994). Cellular automata and complexity: collected papers (Vol. 1). Reading: Addison-Wesley and available online at http://www.stephenwolfram.com/publications/cellular-automata-complexity.

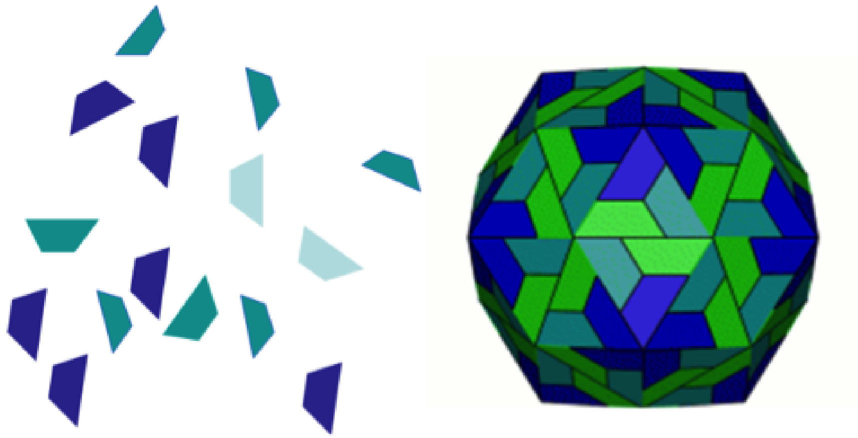


Figure 2.16: Self-assembly of a plant virus (cowpea mosaic virus) shell (capsid) from 120 protein building blocks.[37]

General Motivation

As human beings, we do not think of ourselves as a collection of many cells, but as sentient organisms with dreams and purposes. In this regard, cells—especially the artificial ones we discuss in this section—are but a means to an end. In this Study, we are concerned with establishing an energy infrastructure. Cells are not only a potential means of achieving this end, but due to the need to embed other functions associated with "care and feeding" (setup and maintenance), they bring opportunistically a modicum of intelligence (computation, memory), communications (both locally between cells and globally to allow command and control), and the ability to bind physically (if not support active locomotion). These characteristics can be expanded further to create other types of infrastructure that serve mission-relevant support beyond that minimally necessary to foster the establishment of cellular structures for the base energy infrastructure.

The primary motivations for cellular designs are:

- Inherent flexibility (aided by reconfigurability and multifunctionality) to build an infinite variety of structures from a small palette of individual cell types
- Composeability
- Scalability
- Potential defect/fault tolerance
- Ease and speed of construction (potentially enhanced through self organization)

[37]Lyke, J. & Pugh, R. (2008) Cellular Satellite: A Different Kind of Final Frontier. Proc. AIAA Small Satellite Conference.

Cellular Systems as a Disruptive Technology

The concept of disruptive technology is based on the work of Clayton Christensen.[38] While we can describe the characteristics of disruptive technologies, we cannot always identify a particular concept as being "disruptive," simply on the basis of it possessing these characteristics. It is often only in retrospect that we come to understand that some of society's prevalent concepts (such as the personal computer) had their basis in the humble beginnings as a disruptive technology.

In the developmental ecosystems that give rise to disruptive technology, we seek to improve the state-of-the-art in dominant mainstream approaches (sometimes referred to as incumbent technologies). Many ideas (good and bad) are tried, and most of them are shuttered, never seeing the light of day. Even though some of these ideas are better than even the incumbent approaches, they are considered too impractical or too expensive to sufficiently mature to be competitive. Some of these ideas work, but seem at first at least to be far worse than the incumbent ideas that they compete with.

If, however, some of these "shelved ideas" had been properly nurtured we might find that over time they perform better and improve faster than the incumbent technologies, so much so that they eventually eclipse those older mainstream ideas. This phenomenon (Figure 2.17) is the key behind disruptive technologies. These technologies are not always appreciated by the companies that study them, who often discard them long before their disruptive potential becomes clear to the competitors and startups that bring them to market. In a number of cases where they are brought to market, they eclipse and displace the previous incumbent technology. Since not every possible technology is disruptive, it is easier to simply dismiss entire bodies of research than to devote the potentially significant amount of energy required to curate and nurture the most promising gems. This explains why, paradoxically, many of the disruptive technologies that eventually eclipsed incumbent mainstream approaches were also funded (and ignored) by the companies who competitively suffered from their eventual success.

Cellular technologies, if they succeed, will do so under a disruptive model. Their competition, which is the traditional method of optimized, protracted, customized system development seems so clearly better as a method of building systems today that the cellular approach is at best a novelty. In Figure 2.17, therefore, the traditional method plays the role of "sustaining technologies," while the cellular method plays the role of "disruptive technologies." Through additional investment technology, however, the gap between the two can be brought down. Overhead and efficiency may not be the best measures of potential; rather, flexibility, scalability, defect tolerance, and possibly other metrics may be preferred. These qualities are not considered as important in the present sustaining technology because this model serves us well today, and some see no need to alter it as our ambitions scale to interplanetary destinations.

[38] Christensen, C. (2013). The innovator's dilemma: when new technologies cause great firms to fail. Harvard Business Review Press.

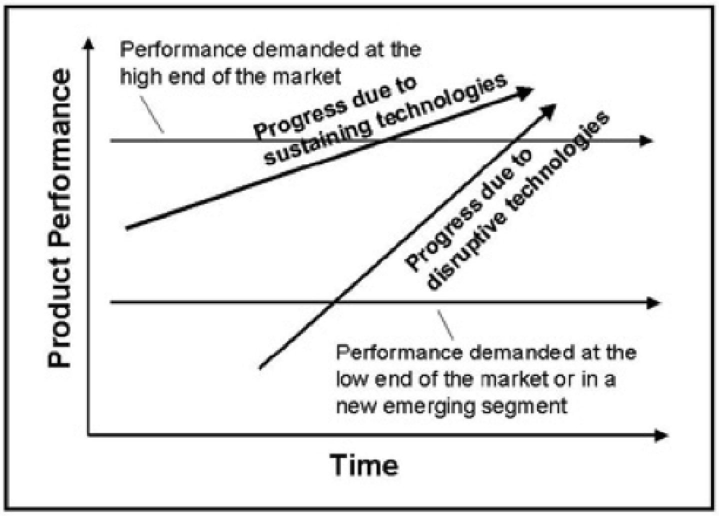


Figure 2.17: Product performance of sustaining and disruptive technologies.[39]

Mission Motivations

The use of the cellular building block system is prospectively attractive for interplanetary applications because it allows for maximum flexibility in forming a variety of structures in orbit and on planet surfaces, particularly when (1) any indeterminism exists in the number, size, and shape of desired structures exists; (2) there is a possibility of repurposing structures; (3) increased adaption is desirable to accommodate defects, faults, and hazards.

For this Study, we envisioned opportunities for cellular structures in the mission roles detailed below. We believe reconfigurable cellular systems can be formed in ways that are robust, adaptive, and scalable, leading to concepts that are compelling when considering mission designs for remote and inaccessible destinations.

2.2.1 Surface applications

Energy Infrastructure

An energy grid could be formed on planetary surfaces as a ground network of energy-harvesting cellular sites. This concept is superficially suggested by Figure 2.18, which depicts a "fabric" formed with a cellular construction. The fabric—comprised of a number of nodes dropped densely on the surface and interconnected—forms the energy infrastructure.

[39] Ibid.

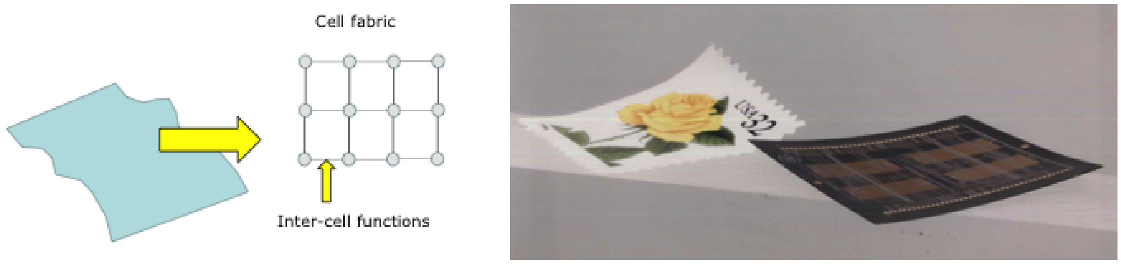


Figure 2.18: Fabric construction as a set of interconnected cellular sites.

The nodal sites, as part of the cellular network, could serve as the basis for an energy, communications, processing, and sensory infrastructural network. They could be considered an artificial type of terraforming, as an attempt to provide energy and data networking grids analogous to those that exist on our own planet. Ostensibly, these sites could be planted, augmented, and reused indefinitely as our ambitions to explore the solar system progress.

The key idea involves creating a day/night energy-harvesting cell capable of providing constant energy in the form of heat and/or electricity. Each cell itself is a system, and the array of cells can connect and aggregate the collection, storage, and distribution of energy. They would connect to "wireless" sources of power on planet (e.g., possibly below the surface) and off planet (direct or relayed solar power), as well as communications (namely the type of command, control, and data infrastructure needed to effectively conduct missions). The harvested energy is invested in missions. While the mission could itself contain a cell, it is compelling to consider keeping it separate from the energy generating cell, so that the harvesting cells/fabrics can be a persistent service, in the spirit of an enduring infrastructure, for exploitation augmentation in the future by variety of missions. These might dock to a multiplicity of cell sites that have been pre-placed in regions of interest and potentially further augmented over time, analogous to the phased upgrades of terrestrial energy grids.

As the basis of an energy infrastructure, these deployed fabrics would be harnessed by future missions, as suggested in Figure 2.19. The fabric would supply a basic set of services to these future missions, including energy, communications, and computation. It would all depend on a viable (cellular, modular, and scalable) energy-harvesting core concept, around which the other cellular service concepts could be infused.

Habitat Construction

Although beyond the scope of the present Study, cellular tiles and blocks seem a heuristically viable methodology for constructing all manner of base structures in support of subsequent crewed and robotic missions, in conjunction with and separately from the energy infrastructure role.

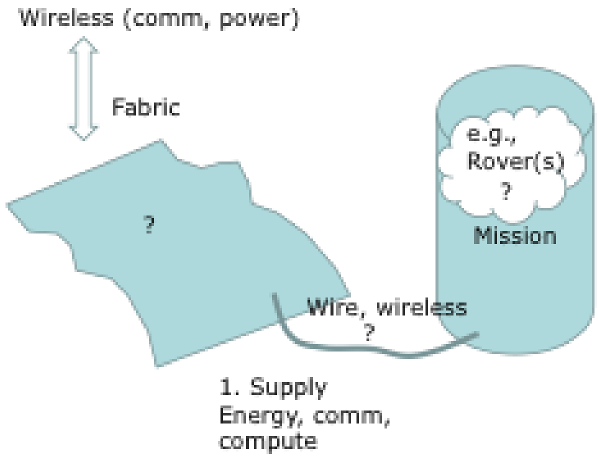


Figure 2.19: Simplistic depiction of energy-harvesting scheme based on a cellular fabric. Cellular fabric is powered remotely. Missions tethered to the fabric can draw power and communications (and possibly other services).

2.2.2 Orbiting Applications

A variety of cellular structures can be formed by deploying a quantity of stowed cells/tiles to self-organize into structures on orbit. In principle such structures would be indefinitely scalable, permitting their augmentation by future missions to form larger structures for energy, communications, or space stations in general.

Energy Capture Through Scalable Solar Arrays

Cellular designs seem naturally suited for creating scaled solar panels. Solar panels are essential in most spacecraft designs, except the very few that have been based on nuclear power. They have typically been body-mounted or deployed, the latter being necessary to overcome the surface serial limits of body-mounted designs. Large spacecraft employ correspondingly large solar "wings," in which the goal is to optimize the ratio between deployed surface area and stowed volume. Custom-built and optimized deployed structure designs would undoubtedly outperform a cellular version since cellular designs would carry additional overhead. However, the cellular design permits a greater variety of shape configurations, scalability due to the ability to cascade a theoretically unbounded number of cellular units, and flexibility to accommodate damage after deployment.

Energy Redirection

One exciting possibility identified in this Study is the redirection/concentration of solar energy, possibly through a chain or relay of orbital sites, to surface points, which can harvest the energy for a variety of mission purposes. The cellular design could improve flexibility for steering and focusing light energy by programmably changing physical conformation of the overall structure as a set of primitive, cell-by-cell, shifts in position and angle.

While the simplest approach involves steering and refocusing light energy from the Sun, there may be advantages in re-radiating the energy in microwave form. In this case, cells would carry the ability to translate photovoltaic energy into radiofrequency form, and transmit the energy (presumably through efficient solid-state power amplifiers embedded in the unit cell) either directly to the surface or to other points in orbit.

Communications Apertures

Cellular designs permit the distributed formation of communications apertures, in which antenna as well as receiver and transmission electronics can be amortized across a number of tiles. With reconfigurability, both dense and sparse apertures could be formed using cellular designs, providing flexibility for communications and radar applications.

> ***Cellular Systems Connecting Concepts.*** One of the important ideas that underlies cellular systems is the notion of local connectivity between neighboring cells. In the formalism of cellular automata (see Section 2.2.3), complex behaviors of entire systems can be coordinated through an ensemble of primitive interactions over time. This means that each cell can only connect to its nearest neighbors, as suggested in Figure 2.20(a). This is an unnecessary restriction, as we often have the ability to broadcast signals over a large group of nodes (Figure 2.20(b)). Nevertheless, being able to design a system in which collective behavior can be specified by local interactions is useful. In the case of remote planetary exploration, a set of widely dispersed cells may degenerate to local-only (nearest neighbor) connections. We also must anticipate defects in the structure of the network, including missing links and missing nodes. These and many other departures from the ideal mathematical abstraction of cellular automata will necessarily occur in real life and must be accommodated.
>
> For this Study, we are concerned with cellular systems based in two different regimes: tightly-coupled and loosely-coupled.

Tightly-Coupled

The tightly-coupled regime refers to cellular structures that are in close physical proximity, based on regular tessellations or tilings. In one dimension, this condition forms a string or strand, while in two dimensions it amounts to the tiling of the surface, either a flat floor or a curved surface as in the capsid of a virus. In three dimensions, it amounts to a stacking of blocks, spheres, icosahedrons, etc., to form crystalline structures. Even in the tightly-coupled regime, we can

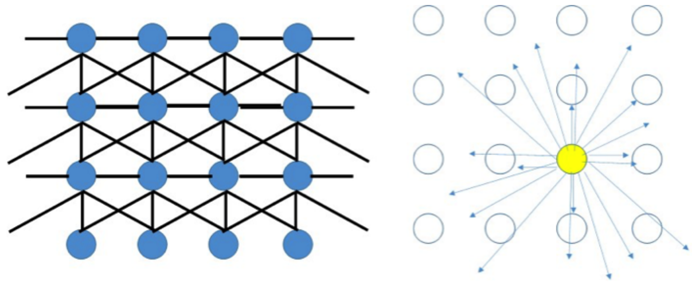


Figure 2.20: (a) Local cellular connectivity. (b) Long-range connectivity (not locally confined).

depart from purely periodic order, leading to tangles, braids and knots (1-D), aperiodic tilings (2-D), and quasi-crystalline structures (3-D). Periodicity can be disrupted in other ways through defects, and the design of cellular systems can take these departures from ideality into account.

In our spacecraft applications, the tightly-coupled regime corresponds to fully-connected aperture surface designs and the formation of other structures. In Lyke and Pugh (2008),[40] structures formed through the connected arrangement of individual tiles (each tile being called a "protosat") were referred to as "macro-sats." Figure 2.21 illustrates these concepts.

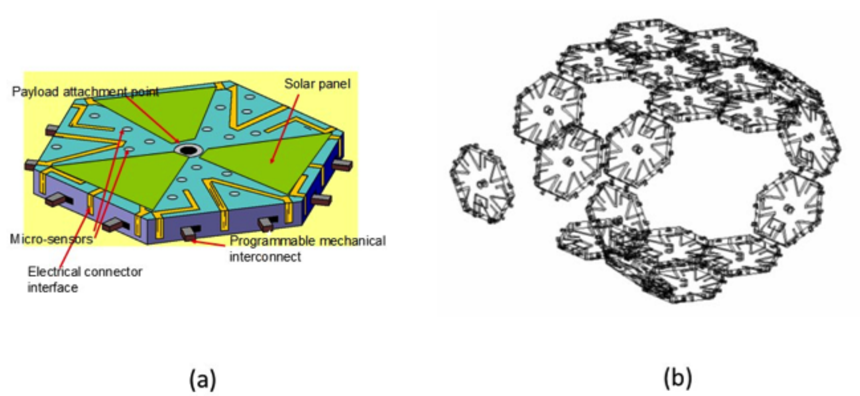


Figure 2.21: Tightly-coupled cellular construction method for spacecraft. (a) Fundamental cell, referred to as a "proto-sat." (b) Partial formation of larger spacecraft structure, referred to as a "macro-sat."[41]

In the tightly-coupled regime, a nontrivial large structure is formed through a deliberate arrangement of primitive cell types. In the homogenous case, the cells are identical, whereas the heterogeneous case involves non-identical cells—a useful case as it allows for tile specialization (a pallette or library of different cell types). Even with reconfigurable multifunctionality, it is likely that not every function will be available in every tile. Some tiles may, for example, may support a

[40] Lyke, J. & Pugh, R. (2008) Cellular Satellite: A Different Kind of Final Frontier. Proc. AIAA Small Satellite Conference.

[41] Ibid.

higher concentration of energy storage, while others may have more advanced locomotion features. In either case, we can consider the global specification of the structure to be a type of digital DNA. The DNA in this case provides the blueprint of a complete system, and in self-assembly it is important to establish mechanisms for geographic (relative location) awareness, to include protocols for intercell communication, selective binding, and resource pooling/sharing.

Fabric-Sat

"Fabric-sat" refers to a continuous sheet of unit cells that are pre-connected and fabricated together in the same overall process. It is a special case of the tightly-coupled regime, requiring no physical self organization. However, many of the concepts for inter-cell communication and collective resource sharing/pooling are applicable. It is convenient to think about a large roll (like wrapping paper or linoleum tile) which could be deployed to form the satellite as a free-standing "smart sheet." In principle, the fabric-sat could be cut into shapes from a larger roll, with the idea that the cells of that contiguous section would self organize to form a collective. These sections could be bonded to other structures as an appliqué, converting otherwise passive structures in effect into a "spacecraft." These sections could be bonded together, presuming that the hooks and connections are made in a proper way, so that multiple sections and rolls can be aggregated to form larger cellular systems.

Loosely-Coupled

The loosely-coupled regime follows the cellular scheme, but works with highly distorted, discontinuous, and irregular neighborhood structure. It may superficially bear little physical resemblance to the periodic order of a traditional cellular automata, but loosely-coupled cellular systems borrow heavily from the many concepts that work well with more tightly-coupled designs, especially the mechanisms for cellular communication and ordering protocols. Whereas we might traditionally expect a tightly-coupled cellular system to drive a recognizable, ordered structure (e.g., macro-sat), loosely-coupled cellular systems can be thought of more as scalable fabrics, having no expected and consistent structure, but working as an ad hoc collective. For the purposes of this Study, we consider the methods for forming energy grids on planetary surfaces to follow the loosely-coupled model. It is possible that the same tiles and protocols can be used in both cases.

Anatomy of a Cell

In this section, we consider the generic anatomy of a unit cell as the building block for the multifunctional, reconfigurable cells that we believe can be used to form an energy infrastructure for the solar system. The ideas described here are of generic appeal, not fundamentally limited to the role of energy infrastructure, as energy is only one of many potential grid-like infrastructure concepts.

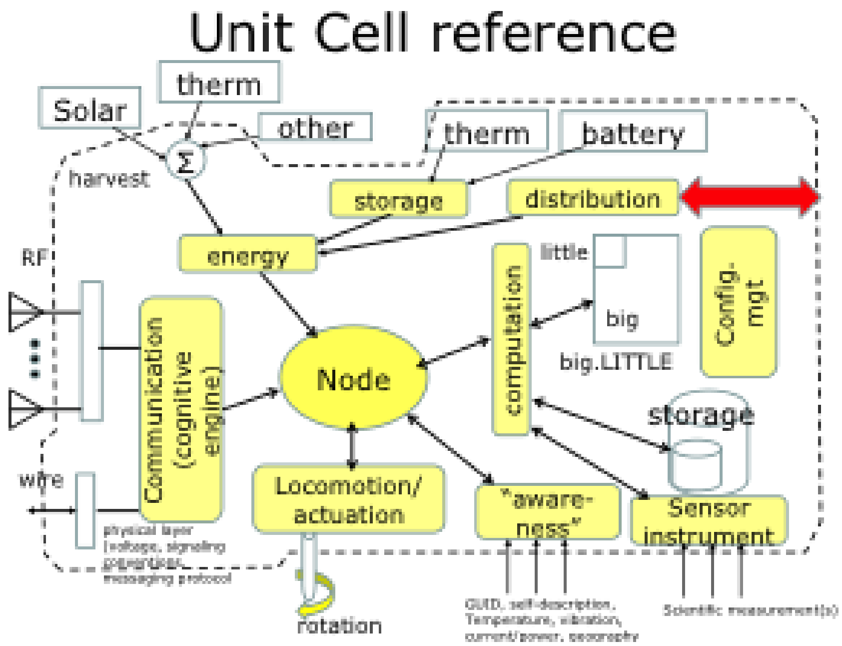


Figure 2.22: Unit Cell as a generic building block for cellular systems.

The basic unit cell reference architecture is shown in Figure 2.22. This is considered a logical specification, not bound to any physical concept. As such, we can consider variations (or adaptations) of this idea for use in one-dimensional (e.g., tensegrity) designs, two-dimensional (e.g., origami, pixelated) designs, and three-dimensional designs. Features of this unit cell will apply in both tightly-coupled and loosely-coupled regimes.

Just as a biological organism can be thought of as having a number of subsystems (e.g., skeletal, muscular, circulatory, etc.), individual cells as well as collectives can be thought of as having a number of subsystems. This section discusses a number of the subsystems associated with these artificial cells.

Electrical power distribution. Power distribution is a fundamental requirement in the concepts pertaining to scalable (i.e., more than one cell) energy infrastructure. The easiest way to imagine this is using a programmable switch matrix and a number of termini present in each cell. The basic concepts are shown in Figure 2.23.

Each unit cell can connect to its nearest neighbors, both mechanically and electrically. Here, we show eight termini capable of accepting or delivering power, two on each edge in a so-called "north-east-west-south" (NEWS) network. This concept can be of course adapted to hexagonal, trigonal, and other two-dimensional shapes, as well as one-dimensional configurations (e.g., termini on each end of a one-dimensional segment) and three-dimensional designs (e.g., termini on "up" and "down" surfaces for cubes, or on other facets for more complex polyhedra). Each participating terminal is routed inside the unit cell to a switch matrix. There are many possible ways for constructing such a matrix, and a schematic of a typical one is shown in Figure 2.23(b). In this case, all termini become rows of the matrix, and columns are wires. Each crossing is a switch point in this diagram, and the schematic equivalencies are shown in Figure 2.23(c).

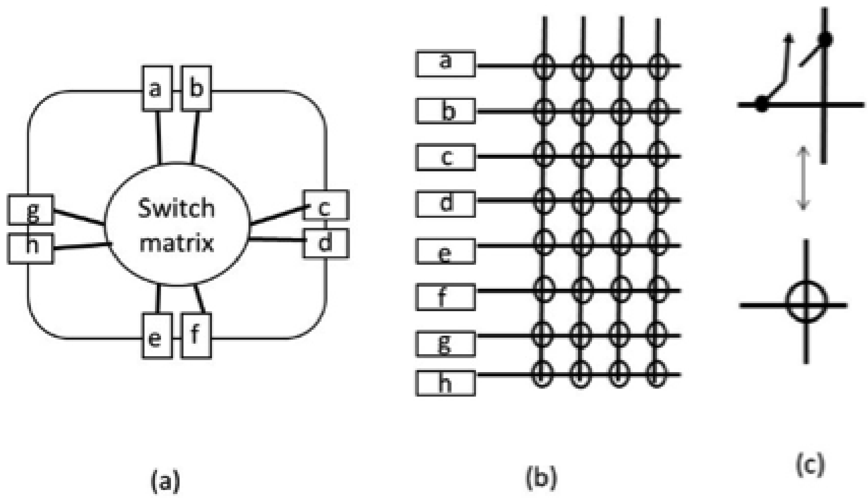


Figure 2.23: Cellular programmable power distribution concepts. (a) symbolic rectangular tile unit cell, having a total of eight power connection termini (two per edge). (b) details of switch matrix. (c) equivalency of circle to programmable switch point.

Figure 2.24 shows how we can programmably route power connections through tiles. For the moment, we are not concerned with internal generation (sourcing) or internal usage (sinking) of power, just transmission. The concept is straightforward, and the same idea works for any type of electrical signal.[42]Hence, these ideas can be extended to route analog, digital, or microwave/radiofrequency signals). If we know which power connections we wish to form, we can establish a netlist (defined as a set of distinct connection specifications). For the problem shown in Figure 2.24, the netlist is a-f, c-e-g, and b-h.

With a netlist specification, we can establish a pattern of "schedule" switch closures that will realize the desired conductivity, as shown in Figure 2.24(b). Since this pattern is programmable, we can define a convention—in particular, a binary juxtapositional notation—that unambiguously translates binary pattern to these switch closures. This is shown in Figure 2.24(c), based on a convention of juxtaposing the Boolean state of

[42]Murray, V.; Pattichis, M.; Llamocca, D.; & Lyke J. (2015). Field-Programmable Wiring Systems, Proceedings of the IEEE, Volume: 103, Issue: 7, Pages: 1159–1180.

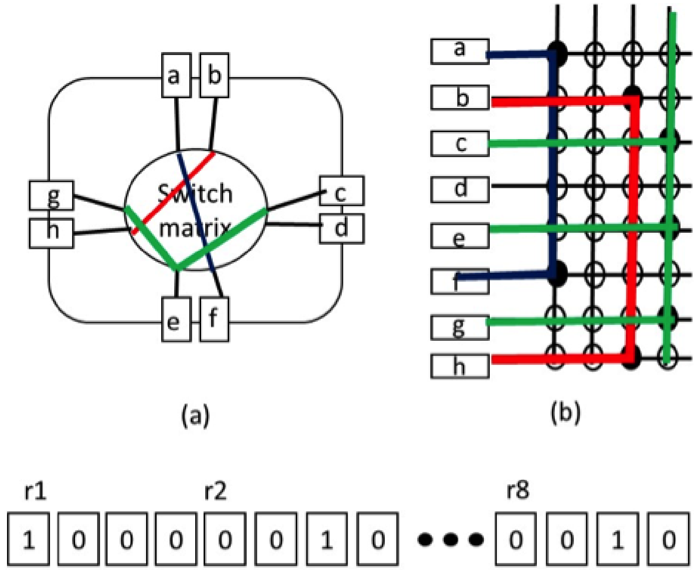


Figure 2.24: Power routing examples in which a unit cell bypasses connections between different edges. (a) Three different connections ("nets") are shown in color-coded form. (b) example solution using switch matrix, with switch closures completing the desired color-coded connections.

each row. In hexadecimal form, we can then specify the pattern as "82101812," and this code can be viewed as a very tiny piece of digital DNA.

Scalability adds another dimension, and an extended, though straightforward, example is shown in Figure 2.25 involving an arrangement of 16 unit cells. In this case, the power routing specification spans multiple tiles. This is a "global specification," which is implemented by translating it into a set of local specifications, each pertaining to a specific unit cell. The unit cells then individually implement patterns as required (following the Figure 2.24 concept) to realize the global wiring solution. There are many possible solutions to this problem, and removing one or more of the unit cells can impact the existence of a global solution. Even so, some tiles can be removed without affecting the existence of at least one solution to the global problem.

Electrical Power Storage. Tiles can contain local energy storage mechanisms, the most common of which is a battery. However, batteries are neither the only storage solution, nor are they always the most effective. In some cases, although energy densities in state-of-the-art ultracapacitors are below those of state-of-the-art batteries, they have the ability to deliver more power more quickly, and may maintain storage at lower temperatures. There are also thermal energy storage concepts that can be converted to electrical power.

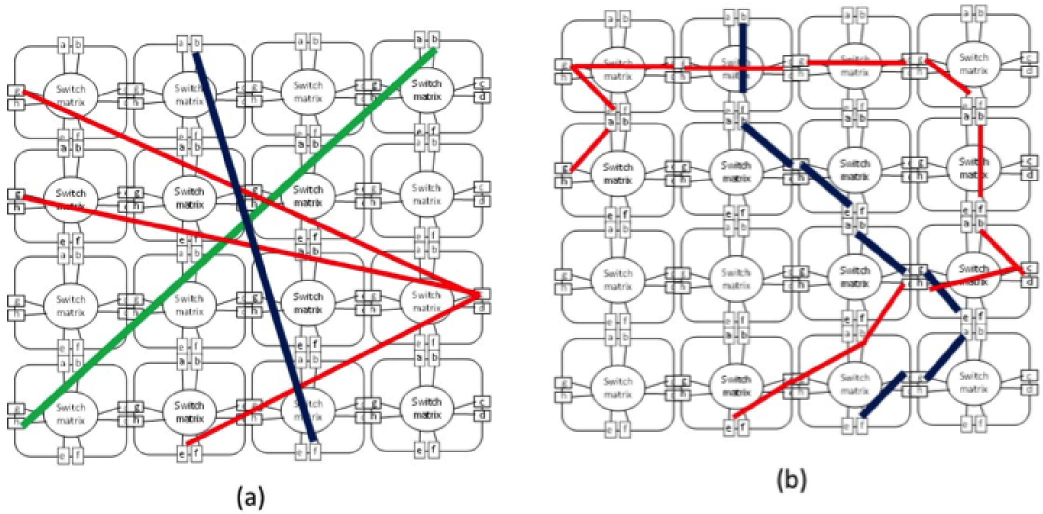


Figure 2.25: Multiple tile power routing. (a) Global specification of a 3-net wiring problem. (b) Translation into (non-unique) set of local wiring specifications.

With these concepts in mind, it is possible to extend the ideas discussed for power distribution to include internal electrical termini corresponding to power storage nodes, thereby extending the switch matrices to accommodate internal connections. As such, it is possible to shuttle power from one node to another, potentially combining these sources to aggregate and deliver power from many tiles to a single point.

Electrical Power Harvesting. Power generation and/or harvesting is an important consideration in tile design. Fundamentally, most power comes from solar energy. On the surface of planets, it is possible to exploit geothermal power, using some type of conduit from the surface to a point below (e.g., a spike) that connects to a thermally stable point. By using temperature gradients, a type of power-harvesting mechanism can be established. Remote planets may offer grim prospects for power harvesting, hence multimodal schemes may be necessary to generate even modest amounts of energy. On planets such as Venus, assuming tiles could be built to withstand a hostile environment, there are many more lucrative forms of power harvesting. In addition to solar and thermal, there are excessive amounts of wind energy, tremendous pressure, and a chemically active/corrosive atmosphere. As in the case of power storage, power generation can become part of the routable grid through accessory interior nodes that augment the routing switch matrices previously described.

Structural. The structural subsystem of the tile simply refers to the tile's physical embodiment. Ideally, tiles are initially dense for efficient stacking and storage. Once deployed, tiles could conceivably expand, if making them thicker provides an advantage for energy storage were structural rigidity.

Programmable Attachment. For tightly-coupled regimes, the notion of programmable attachment becomes an important consideration. Notionally, it is beneficial to have the ability to selectively bind one or more edges of tiles to each other, so as to form structures in deliberate design patterns. We present the basic set of concepts in this section.

There are many possible mechanisms for establishing a programmable edge attachment, but all of the examples presented here use magnets.[43]We specifically allow for two different programmable states, one in which the North Pole of the magnet faces the edge, and the other being the inverse (South pole facing the edge), as shown in Figure 2.26. Other options include mechanical gripping concepts for the attachment, programmable glues based on rapid cure thermoplastics, and other mechanisms. Ideally, the mechanism selected would be reversible, permitting future rearrangement.

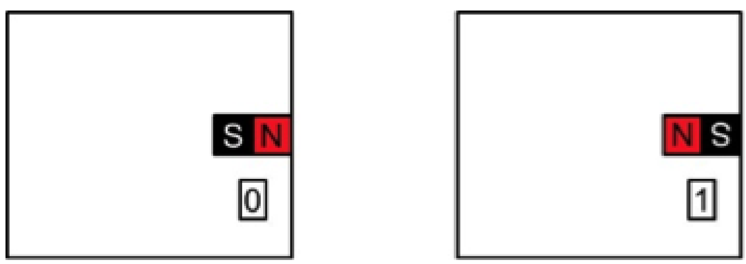


Figure 2.26: Programmable attachment using magnets: (left) default edge state; (right) programmed in version of default state (e.g., edge = "1").

Concepts for programmable attachment are straightforward. As suggested in Figure 2.27, two possibilities are permitted. In the first case, edges may be prompted to attach to each other by ensuring that one tile has a different polarity on its connecting edge than the other tile (Figure 2.27(a)). The other possibility is repulsion, which is done by ensuring that both edges of the same polarity (Figure 2.27(b)). It would be desirable to have a third, simply passive, state (neither attractive nor repulsive), and that concept would be a simple extension of the ones shown here. For example, in the

[43]Note that magnets are only shown for illustrative purposes, in that it is possible to replace magnets with other concepts, such as MEMS-based Velcro-like grabbing actuators, programmable glue based on a combination of thermoplastic materials and switchable heaters, etc.

case of magnetic attachment concepts, a passive "stickiness" could be implemented by permitting a half rotation, as suggested in Figure 2.28.

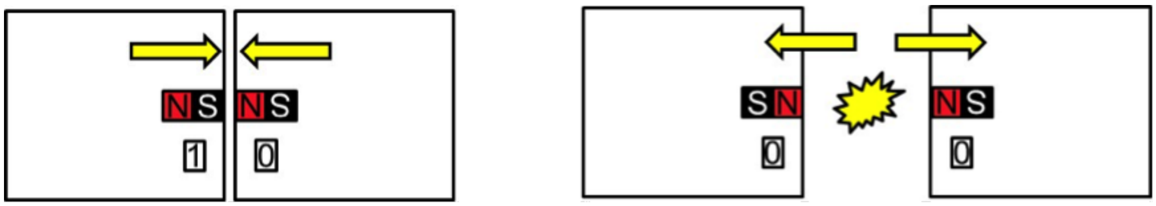


Figure 2.27: Programmable attachment using magnets: (left) attraction between edges; (right) repulsion.

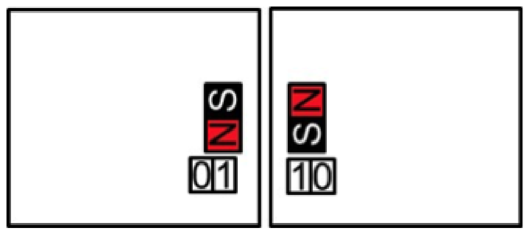


Figure 2.28: Passive "stickiness" using programmable attachment based on magnetic force, requiring 2-bit Boolean state to encode a third condition.

Extensions of the single-edge programmable connection are shown in Figure 2.29. As before, these illustrative examples are based on square geometries, and of course they could be extended to other polygonal (polyhedral for 3-D cases) geometries. Each edge/facet supports programmable attachment. As in the case of the routing matrices, it is convenient to encode the state of edges for programmable attachment as a binary vector using juxtapositional notation. We can define a default stickiness case ("0000" or 0 hexadecimal), and set bits accordingly.

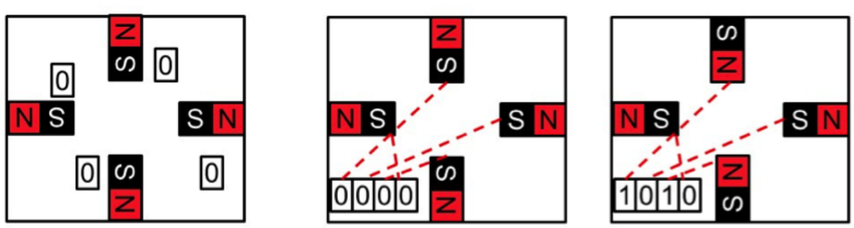


Figure 2.29: Extensions of the single-edge programmable connection.

Programmable attachment is only practical for the ensemble (multi-tile) case. One configuration is shown in Figure 2.30(a), with the equivalent numerical representation of a multi-tile ensemble shown in Figure 2.30(b), based on the conventions illustrated in Figure 2.29. With these established conventions, it is necessary to program several cell states in order to have a stable structure. In other words, the default state (0000) will cause all tiles to repel on all edges.

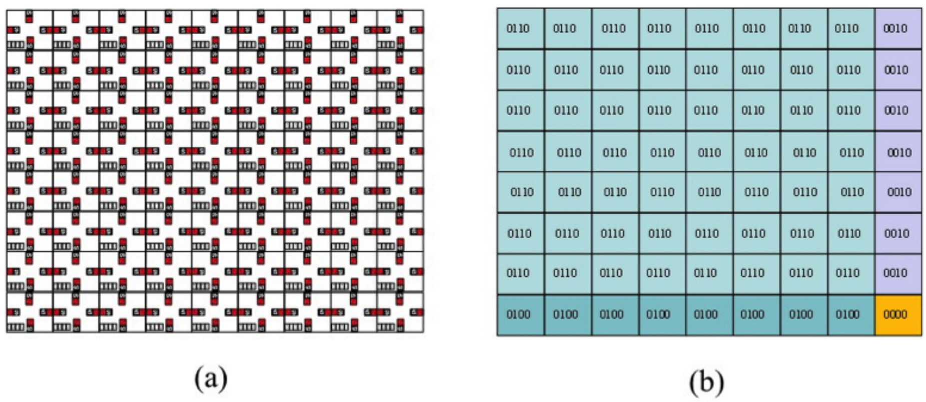


Figure 2.30: Tile ensemble supporting programmable mechanical attachment. (a) 8x9 ensemble. (b) equivalent numerical representation.

Based on this scheme, we adopt a notion of "right stickiness" and "bottom stickiness," which leads to compact formula set. All tiles use "formula" or "rule" 0110 ("stick right," "stick bottom") unless:

- Right edge: terminate right stickiness. In this case, we set the local rule = 0010
- Bottom edge: terminate bottom stickiness. In this case, we set the local role = 0100.
- Bottom right corner: it is necessary to terminate the stickiness (i.e., "stop the sticky") by using the default rule = 0000.

These are the conventions necessary to make contiguous planar surfaces. Of course, nontrivial possibilities can be accommodated by appropriate rule configurations in the different tiles forming a complex structure. One example of the planar structure with "knockouts" is shown in Figure 2.31.

Intelligence/Computation. Even the most rudimentary of the features described requires some digital intelligence to manage state, mediate local and global rules, and handle other care and feeding issues. This could be accommodated by a very simple microcontroller, enriched with a special type of distributed software framework that allows extensions, scaling, and handles faults/defects in the cellular structures and systems formed.

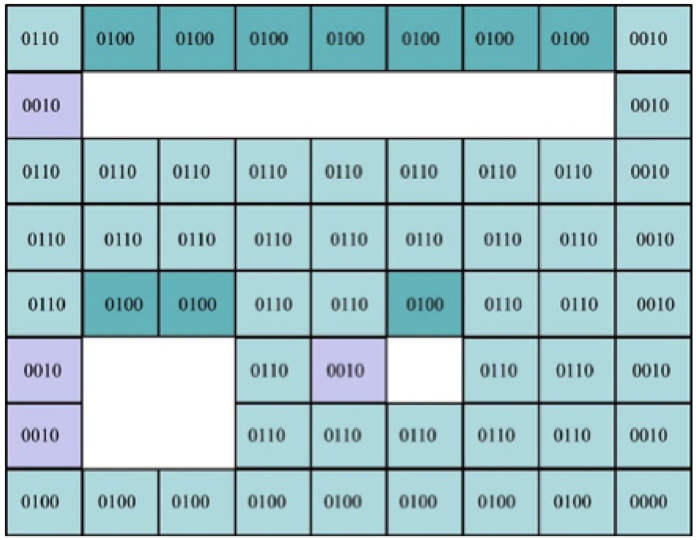


Figure 2.31: Planar tile surface with three "knockouts" formed by rule conventions.

Communications. Communications infrastructure involves the use of reconfigurable antennas, which can be formed by a distribution of conductors connected by switches that could be set in a manner similar to that described for electrical power distribution and programmable stickiness mechanisms. Each cell would require a flexible software radio-based transceiver concept and ideally, the cells could work alone, in combination, and in phased arrays.

Sensory. A number of sensing mechanisms are required in the cellular unit cell to accommodate essential care and feeding, such as a variety of thermal sensors, current monitors, pressure sensing, and other mechanisms to ensure proper functioning of other subsystems. Additionally, other sensors could be embedded in the unit tiles to provide useful science, and to support other interesting mission objectives. These range from the symmetry and analytic science instruments, to more sophisticated cameras, vibration sensors, and other devices. In principle, the communications subsystem could be fashioned into a rudimentary microwave radar, and distributed tiles could use a number of mechanisms if they possess precision timing facilities (such as chip-scale atomic clocks) to create a basic ad hoc implementation of the global positioning system.

Locomotion. Locomotion may be an important concept in some of the cellular tile concepts. It is not absolutely essential, however, nor is it essential that all tiles carry locomotive facilities. Self-organization and self-assembly can exploit a number of passive principles and rely on achieving useful arrangements based on opportunistic motion, such as a mechanisms used by some simple viruses which rely on ambient energy for transport.

Reconfiguration and Configuration Management. We have already discussed a number of reconfigurable subsystems, in which state information is conveyed through a Boolean string. In general, an entire unit cell is the juxtaposition of many sections of Boolean strings that specify the settings of these reconfigurable subspaces. Hence a local tile essentially possesses a local digital DNA. The global configuration of many tiles is, at one level, the collection of all local digital DNA substrings, with additional information governing the positions of each local tile within the global construct. There are many interesting research problems that could be explored in a straightforward manner. It is not clear, for example, if it is necessary to rigorously specify all local digital DNA settings. As we have seen in the case of power distribution, there are, for example, many non-unique ways of specifying power arrangements. Locking these down as permanent patterns restricts flexibility. Hence, we are more interested in specifying the global netlist as part of the digital DNA specification, and equipping the collective to cooperatively solve the non-unique local specification problem. Moreover, we are interested in a degree of robustness, such that if we lose local tiles for any reason, the collective can attempt to resolve the global problem and generate new local subproblems.

Structure. There are many possible ways of constructing the unit tile. One multilayer approach might be based on the following conventions:

- **Top layer:** a thin, transparent photovoltaic sheet (permitting capture of visible and infrared sunlight).
- **Second layer:** a thin, transparent sheet printed with a variety of antenna geometries, interconnected by PIN diodes, MEMS switches, or other electromagnetically suitable switching mechanisms.
- **Third layer:** contains the electronic brains of the operation, with microprocessors, memory, sensors, and transmitters and receivers, both to handle the minimum for care and feeding and additional resources for externally supplied applications. The processes would run a lightweight but powerful software architecture capable of managing distributed systems and managing local interpretation of global rules and configuring tile internal subsystems
- **Fourth layer:** possibly a thermal regulation/storage system
- **Fifth layer:** provides for power storage and distribution resources.
- **Sixth layer:** supports physical accommodations for programmable attachment

and optional deployments of standoffs and/or a mechanical structure to form a 1m length spike, which could form the basis of the geothermal energy harvesting concept to exploit the energy differential between the surface and the soil a meter down. The burrowing concepts, efficacy of the approach, and potential problems require further study.

Cell Specialization and Heterogeneity

The concepts described here so far assume a homogenous reconfigurable unit cell. It is possible that some tiles may have more wiring resources, more computation, more sophisticated radiofrequency facilities, etc., and it is straightforward to consider heterogeneous arrangements as mixtures drawn from a library of cell types. We do not believe that this requires the introduction of new concepts, but careful thought in terms of physical design, as well as the ability to accommodate heterogeneous bitstring specifications for the different tiles. If, for example, there are five different tile designs and each is capable of doing some routing, it is important to understand these differences as global routing is mapped to local (non-uniform) cell types.

2.2.3 Appendix: Theoretical Underpinnings of Cellular Architectures

Cellular automata are mathematical abstractions studied by von Neumann and Ulam,[44] with a resurgence in popularity due to the work of Wolfram.[45] It has been said that von Neumann, whose name is associated with the stored program computer (itself a hardware embodiment of the Turing machine), actually envisioned the construction of computers based on the cellular automata model.

Example of Elementary Cellular Automata

Cellular automata (CA) are characterized as a periodic array of computing points. The simple example in Figure 2.32 will make most of the basic concepts clear. Figure 2.32 illustrates a one-dimensional binary cellular automata: a string of equally spaced computing points. Each point on the string can have a value of {0} or {1}. The value of each site is updated at discrete time intervals. The updates are computed as a function of a local neighborhood, which corresponds to the immediately adjacent points to the left and right, along with the value of the point in question itself. This particular CA has been extensively studied by Wolfram, who sometimes calls it an "elementary CA."

[44] Von Neumann, J., & Burks, A. W. (1966). Theory of self-reproducing automata. IEEE Transactions on Neural Networks, 5(1), 3-14; Pickover, C. A. (2009). The math book: from Pythagoras to the 57th dimension, 250 milestones in the history of mathematics. Sterling Publishing Company, Inc.

[45] Wolfram, S. (1994). Cellular automata and complexity: collected papers (Vol. 1). Reading: Addison-Wesley and available online at http://www.stephenwolfram.com/publications/cellular-automata-complexity.

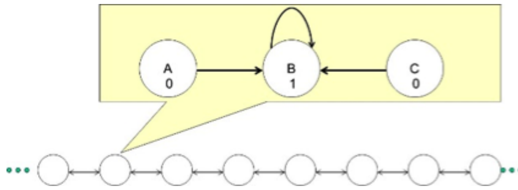


Figure 2.32: Elementary cellular automata (CA).

Since the value of each point depends only on a small neighborhood around the point, we can easily and rigorously specify the behavior the CA by stating the next value based on all possible combinations of the value of the neighborhood. This idea shown in Figure 2.32.

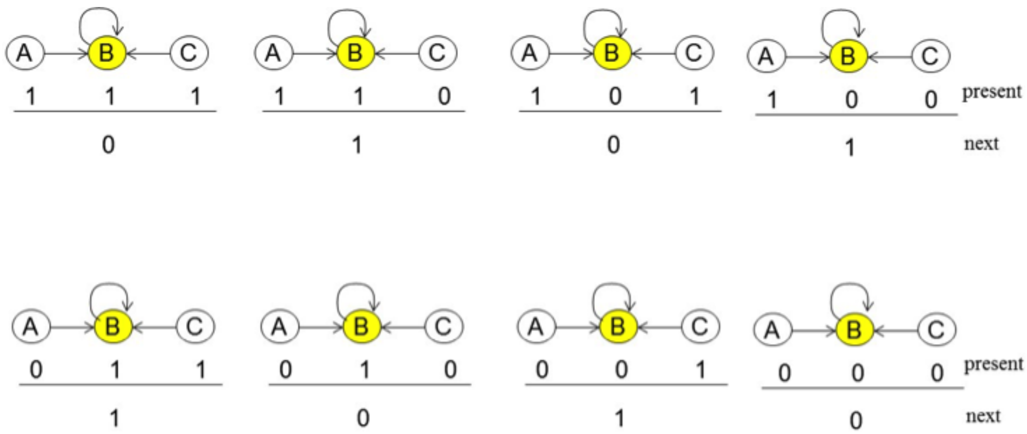


Figure 2.33: Illustration of the Rule Number procedure.

It is easy to show that the information in Figure 2.32 can be collapsed to a single number using the procedure illustrated in Figure 2.33. This procedure simply renders the value specified for each combination of neighborhood value into a compact juxtaposition. This is sometimes called the rule number (Rule 90 in the example shown in Figures 2.33 and 2.34).

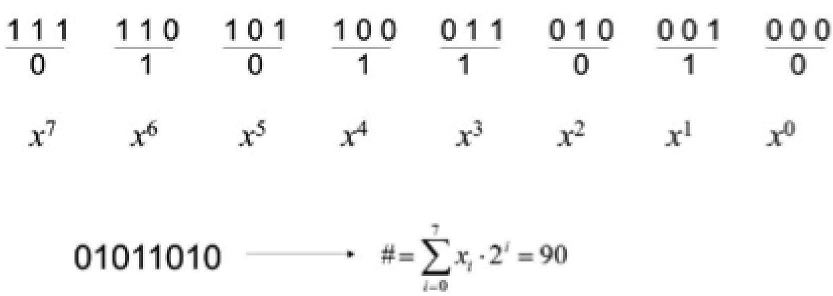


Figure 2.34: Rule Number (Rule 90).

Wolfram studied elementary CA by using a strip-chart-like concept in which the value of an entire CA structure becomes a row in a table. Each successive row below represents the value of the same CA structure for another time step. This spatiotemporal diagram is shown for a small CA structure in Figure 2.35 (this time with Rule 150 instead of Rule 90, and using colored points (beads) instead of numbers).

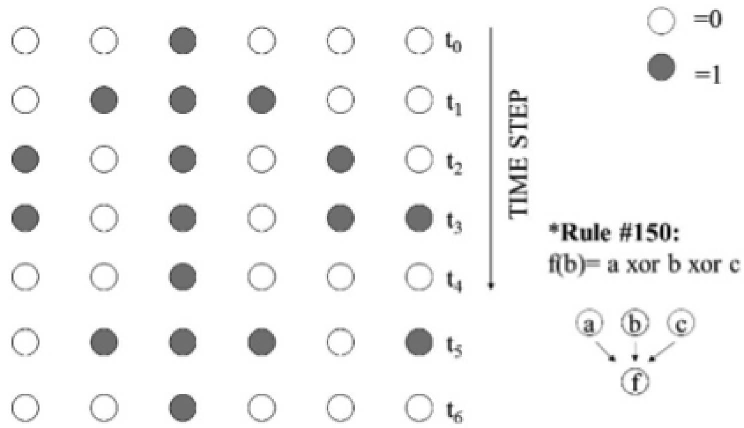


Figure 2.35: Spatiotemporal diagram for a small CA structure.

In this case, the initial value of the CA structure is uniformly 0, except for a single bead which is seeded with value 1. A slight extension of this example, shown in Figure 2.36, clearly depicts a fractal structure. By changing the rule, using the same initial condition, a great variety of intriguing patterns (as well as uneventful ones) can be elicited. While CAs evolve their values based on calculations that are only local to each point, a large CA structure may demonstrate behavior of global significance. As a result, even the simple cellular automata have been extensively studied for the last several decades, and Wolfram showed that one rule (Rule 110) is capable of Turing complete (arbitrarily sophisticated) computation.

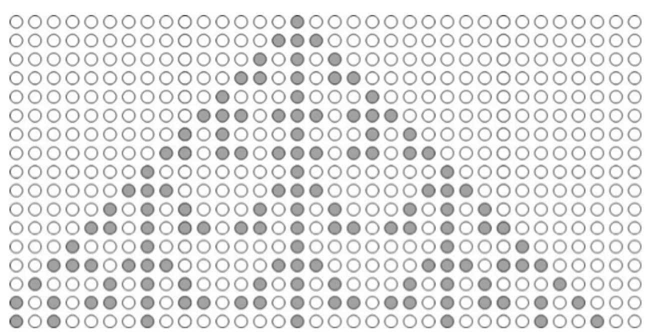


Figure 2.36: Spatiotemporal diagram for a fractal CA structure.

Some Properties and Extensions of Elementary Cellular Automata

While a full discussion of cellular automata is well beyond the scope of the present report, it will be useful to briefly discuss a few more concepts, as these will correspond to ideas discussed in terms of multifunctional structures.

Dimensionality and Finiteness. While we will be concerned with arrays corresponding to spatial dimensionality (i.e., 1 to 3 dimensions), CAs can be in an arbitrarily high dimensional space, and in an abstract way they are infinite in extent. For finite structures, two broad cases exist for handling the edges: (1) null-terminated and (2) circular boundary conditions. In the former case, the behavior of CA structures simply stop at the edge. In the latter case, signals are wrapped around the edges. The behaviors of some CA structures can show marked differences by altering the boundary conditions between these two cases.

Homogeneous and Heterogeneous Rules. In the simple CA structures discussed so far, each site is assumed to have identical functions or rules that specify its behavior, corresponding to the homogenous case. With heterogeneous rules, much more sophisticated global behaviors can be extracted from the CA structure. By making it possible to specify the rules of any CA site, we are creating a very simple type of reconfigurable cellular structure (where each cell is implemented as a simple lookup table memory), an idea of fundamental importance to the architectures we wish to create. While it is possible to achieve powerful results with homogenous, statically-defined rules, the ability to tailor rules and in some cases make the definition adaptive, allows for more complex behaviors with more compact CA structures. There are several notional strategies for heterogeneity, ranging from simply establishing alternations of rules in some periodic fashion within the also periodic structure of a CA to a full-blown ability to arbitrarily set any rule for any CA site to any value (the most general case).

Values of CA at Each Site and CA Expressiveness. In the most elementary CA structures, the value assigned to each site is confined to a Boolean value (0 or 1). In principle, the value at each site can be multi-valued (3 or more states, to a continuum limit) and vector-valued (each site maintaining a group of values). As we increase the number of admissible values at each CA site, the notion of simple rules (essentially a state transition matrix) is no longer adequate, and more complex functions must be used to describe CA behavior. For vector-valued CAs in particular, it is necessary to consider a vector (grouping) of multiple (possibly distinct) rules/functions to fully specify the CA structure state at each site.

CA Templates. A CA template is simply the specification of the unit cell of an extended CA structure. This can be shown schematically as in Figure 2.37, which depicts a number of neighborhood template structures. Figure 2.37(a) depicts the template schematic for the elementary CA discussed earlier. Figure 2.37(b) depicts the

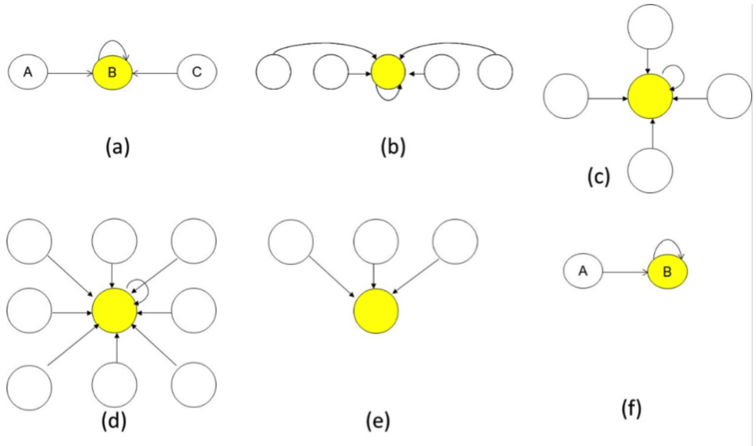


Figure 2.37: Neighborhood template structures.

template of a similar CA which only differs in the size of its neighborhood (radius $r = 2$ instead of $r = 1$). The primary difference between 2.37(b) and 2.37(a) is that the rule number expands from $2^{(2^3)} = 256$ to $2^{(2^5)} = 4G$ (2^{32}), and the size of the lookup table to implement a configurable rule grows from 3 inputs to 5 inputs. The next three templates correspond to two-dimensional CAs. Figure 2.37(c) corresponds the template structure used in the CAs from Conway's "game of life."[46]In this template, the neighborhood is $r = 1$, but corners are excluded (known as a "von Neumann" neighborhood). Figure 2.37(d) is the same template with the corners included (known as a "Moore" neighborhood). If we use the spatiotemporal diagram itself as a template structure, we produce a special but limited form of 2-D CA shown in Figure 2.37(e) referred to as a "one-way" CA because signals can only propagate in one direction. Figure 2.37(f) is a one-dimensional version of a "one-way" CA.

Relaxing CA Templates. It is useful, especially as we consider exploiting CA concepts in the real world, to consider how we might relax some of the rigidity of CA principles while still extracting some of the benefits of CA concepts. For example, in mathematical CAs, structure is always periodic, the nearest neighbor connections are rigidly local and confined to a specified neighborhood size, and all sites are perfect. There are a variety of interesting ways in which these rules can be relaxed. For example, we might consider "mostly periodic" CA templates, where sites might wander or even be absent within a larger CA framework (corresponding loosely to the idea of defects or faults and structure). We might consider that while most of the time all CA sites connect only to nearest neighbors, perhaps once in a while the links jump to more

[46]Gardner, M. (1970). Mathematical games: The fantastic combinations of John Conway's new solitaire game "life." Scientific American, 223(4), 120-123.

distant neighbors. If we assign probability functions to neighborhood relationships, we can express networks that in some sense are more powerful, in which the number of hops—and therefore latency/bandwidth between arbitrary points—might be reduced.

At some point, relaxing enough aspects of the "cellularity" of CAs yields structures that bear little resemblance to the CA ideas that may have inspired them. This is not altogether a bad thing, however, as there is utility in CA concepts that have been warped to some degree to yield other benefits. For example, in an "internet of things" system involving many small simple nodes that are wirelessly connected, we might be able to interpret the network as a type of relaxed CA. Since the neighborhood is defined wirelessly, it could be viewed simply as a nominally periodic network that retains many of the other features of the CA structure.

2.3 Terrestrial Solar Technologies: Applications for Energy-Rich Environments

Solar radiation at Earth's surface is fairly low in terms of power density (850-1000 W/m^2). It is also subject to day/night cycling and fluctuations due to weather/environmental conditions. Even in the sunniest places on Earth, the energy delivered might be $\sim$3500 kWh/m^2/year. That means a square meter of solar panels, tracking the Sun in the desert over a full year might receive the same amount of energy contained in 100 gallons of gasoline. Conversion of that sunlight into electricity by standard terrestrial solar panels is $<=$ 20% efficient using current technology.

In space, (at distances from the sun comparable to Earth's), there are some advantages to solar power: we no longer have to worry about weather, and the insolation is $\sim$30% higher due to losses in the Earth's atmosphere. Properly placed and controlled solar panels might see the full 1300 W/m^2 of incoming sunlight more than 90% of the time, for an annual energy input of $\sim$10,000 kWh/m^2/year—roughly 3 times better than the best desert locations on earth. There are also some downsides; most notably, the atmosphere also blocks a lot of harmful radiation that can damage materials in space.

For both space and terrestrial systems, the overall cost for the electricity used, as compared to other sources, has 3 components: total deployed cost of the equipment (generally measured as a cost per watt); the actual resource available at the deployed site (kWh/m^2/day or per year); and the lifetime of the system, including degradation over time and the potential for catastrophic failure of a component of the system.

Herein lies the major difference between a terrestrial and a space based system: for the installed or deployed cost, the equipment and labor is the biggest driver for a terrestrial installation, whereas the launch costs (driven almost completely by weight) are the biggest driver of costs for space systems. This difference has led space solar systems development to prioritize efficiency of the solar panels above all else (including panel equipment and assembly costs), as higher efficiency will lead to lower weight for the same power. In terrestrial solar applications, cost per watt (or per kWh) has been the driver, with efficiency playing some role in driving down overall installed costs, but not as an overriding factor.

2.3.1 Concentrating Solar Technologies on the Ground

Attempts to increase efficiency on the ground by adding complexity to the system—in the form of optical concentration of the sunlight coupled with either high-efficiency cells of the type used in space (concentrating photovoltaics or CPV), or coupled with generators that use the heat generated by the Sun—have struggled to find a place in the competitive market (concentrating solar power or CSP). In both cases, the idea is to couple a more efficient conversion "engine" (e.g., a turbine/generator or similar in CSP and >40% efficient PV conversion in CPV) to the process, using the concentration to help drive up that efficiency and also to reduce the costs associated with the more efficient receivers.

An example illustrating some of the challenges can be seen in the Ivanpah solar thermal power plant in Nipton, CA. This plant produces power by using direct sunlight to heat water in a boiler up to high-pressure steam, which then runs a turbine generator (just as any fuel-fired steam generator would do). Ivanpah has a nameplate power generation of 377 MW. However, historical averages for southeastern CA sunlight show an annual average $\sim$8 kWh/m^2/day of energy in the incoming direct sunlight. The standard power conditions for solar installations (from which nameplate ratings and efficiencies are usually set) is between .85 and 1 kW/m^2, meaning that the plant likely has a capacity factor of less than 33%, and the plant manager cited a rough estimate of $\sim$28%. In other words, the plant's annual energy production is roughly 28% of the production you would get if the plant produced it's nameplate power rating (377 MW) consistently for 24 hours a day and 365 days a year.

In order to generate the heat required to run the boilers, Ivanpah uses fields of mirrors to focus the sunlight down to a very high concentration. By their count, there are 173,000 heliostats (tracking structures that aim the mirrors to capture the sunlight) that each hold 15 m^2 of mirror area. Not counting the spacing between the mirrors, we can calculate an aperture area efficiency (based on the standard .85 kW/m^2 of incoming sunlight) of $\sim$17%. The full area efficiency for the plant would be much lower, but is perhaps not terribly relevant as the land used is not a major cost driver in the desert where the plant is located.

This plant cost an estimated $2.4 billion to build, and although ongoing operations and maintenance costs are much lower than, for example, those at a fossil-fuel plant, they still exist. The installed cost is greater than $6/Watt, although subsidies may have lowered that to $\sim$$4/Watt. In contrast, the utility-scale conventional PV solar installations, after subsidies, can be installed for a cost of $1.68/Watt, a cost that is competitive with a new natural gas plant. This comparison alone demonstrates the challenge that CSP technologies have faced and will continue to face in the terrestrial energy landscape.

2.3.2 Applying PV and CSP Lessons to Space Power Systems

Unlike the terrestrial case, one can imagine real gains that come from lightweight, deployable concentrating optical components. Thinking about the multifunctional tile system at the core of this discussion, a series of "reflector tiles" can self assemble on a tracking structure and direct concentrated sunlight to receiver tiles, which can use either the heat from that system or sunlight to generate electricity in a PV tile (or both). As the number of "power generating" tiles would be relatively small, and the weight of the reflector tiles could be quite low, this opens the possibility of developing an energy-rich environment for surface exploration. The added complexity of coordinated tracking of multiple units, as well as size, distance, and efficiency tradeoffs would need to be explored in detail to understand the power that could be generated and the costs for such a system. In some cases, the non-concentrated solar flux on the surface might be sufficient to generate the required power and heat. In some cases, where there may not be sunlight incident on the surface, or in the case of outer planet exploration where the density of incoming solar radiation may be significantly lower than that near Earth, deployment of concentrators might be necessary.

2.4 Active Materials for Extreme Environments

Actuators are used to drive all active mechanisms including, to name a few, machines, robots, and manipulators. The actuators are responsible for moving, manipulating, displacing, pushing, and executing any action that is needed in the operation of the mechanisms. For planetary applications, actuators perform: mobility, actuation, manipulation, transport, deployment and pointing, folding and unfolding, digging, penetration, sample acquisition and handling (gripping, crushing, etc.), pumping, and many other functions. Some applications require extremely high precision (e.g., optical devices). Each degree of freedom (DoF) of a mechanism typically requires a dedicated actuator, and the complexity increases significantly as the number of DoF rises. In mechanisms such as robots, the mass and volume of the actuators take up a significant part of the total specific system mass and volume. Generally, actuators function as the equivalent of muscles and they are operated by a source of energy (typically electric current, hydraulic or pneumatic pressure) that is converted into motion. The operation of actuators is significantly different than natural muscles, which are both compliant and linear in behavior. The control system that drives an actuator can be a simple fixed mechanical or electronic system, computer driven or operated by a human user. The types of actuators that are generally used include electric (such as AC, DC, brushed and brushless motors), pneumatic, hydraulic, piezoelectric, and shape-memory alloys.

For planetary applications, actuators are used to operate robotic devices as well as space mechanisms and instruments. These include rovers, grippers, drills, release and deployment mechanisms, antennas, positioning devices, aperture opening and closing devices, etc. Increasingly, actuators need to have minimal mass, volume, and power consumption, as well as the capability of operating in extreme environments. The miniaturization of conventional electromagnetic motors (AC and DC) is limited by practical manufacturing difficulties. These electromagnetic motors, which are the most widely used in compact mechanisms, employ speed-reducing gears to reduce speed, which can be as high as many thousands of RPM, to develop a higher torque. The use of gear trains adds mass, volume and complexity and reduces system reliability by adding components. The miniaturization of conventional electromagnetic motors is limited by manufacturing constraints and loss of efficiency. Furthermore, conventional actuators are backdrivable making high precision control difficult to obtain or necessitating additional braking mechanisms, which requires heavy and complex gears to provide the necessary speed and torque.

While electromagnetic motors are used widely, there is a growing use and development of active materials that are mechanically active that are responsive to transducing stimulation. There are many types and principles of actuation that are responsible for producing displacement or physical movements in active materials, including:

- Piezoelectrics:
  - Effect takes place in crystalline materials with no inversion symmetry
  - Linear electromechanical interaction between the mechanical and the electrical states
- Electrostriction:
  - Effect involves deformation of dielectrics in an electric field
  - Result of the induced dielectric polarization
  - Proportional to the square of electric field strength
- Magnetostrictive materials:
  - Convert electromagnetic into mechanical energy
  - Examples: nickel and some of its alloys
- Photostriction:
  - Generation of strain by irradiation of light
  - Can be observed in ceramics, PLZT (made of lead, lanthanum, zirconium, and titanium)
- Electroactive Polymers (EAP):
  - Family of materials that mechanically respond to electrical stimulation

- Shape Memory Materials:
  - Display two distinct crystal structures or phases, which is a function of the temperature and internal stresses
  - Include Shape Memory Alloys (SMAs) and Polymers
- Electrorheological fluids (ERF):
  - Suspensions of extremely fine non-conducting particles (< 50 μm diameter) in an electrically insulating fluid
  - In response to an electric field, their apparent viscosity changes reversibly by up to 5 orders of magnitude and in milliseconds.
- Magnetorheological fluid (MR fluid) and magnetic field
  - Similar to ERF but using magnetic particles.

A comparison of the characteristics of three of the leading active materials is given in Table 2.4.

Table 2.4: Comparison Between Three Leading Transducing Actuators.

Property	Electroactive Polymers (EAP)	Electroactive Ceramics (e.g., piezos)	Shape Memory Alloys (SMA)
Actuation Strain	Over 300%	Typically 0.1–0.3%	$<$ 8% (short fatigue life)
Actuation Stress (MPa)	0.1–25	30–40	200
Reaction Speed	μsec to min	μsec to min	msec to minutes
Density (g/cc)	1–2.5	6–8	5–6
Drive Voltage	Ionic EAP: 1–7 V, Electronic EAP: 10–150 V/μm	50–800 V	5 V
Fracture Behavior	Resilient, Elastic	Fragile	Resilient, Elastic

Ultrasonic motors based on piezoelectric actuation have been available for some time.[47] The mode of operation (quasi-static or resonant), type of motion (rotary or linear), and shape of the actuation element (beam, rod, disk, etc.) can be used to classify the various piezoelectric motor configurations. Despite these distinctions, the fundamental principles of solid-state actuation are common to all of these devices. Each of these motor designs uses microscopic material deformations (associated with the excitation capability of piezoelectric materials), which are amplified through either quasi-static or dynamic/resonant means. Piezoelectric actuators offer attractive characteristics including high torque/force density and the ability to operate at extremely

[47] Uchino K. (1996) Piezoelectric Actuators and Ultrasonic Motors. Electronic Materials–Science & Technology, Kluwer Academic Pub.

high and low temperatures. To compensate for the small electrically generated strain generated by the base piezoelectric material, mechanical leveraging techniques are used to amplify displacements. Over the last two decades, many novel concepts of displacement enhancement have been explored and numerous motor configurations have been developed and demonstrated.

For planetary applications, actuators need to operate at extreme temperatures ranging from as low as -200°C (e.g., Europa and Titan) to as high as 460°C (e.g., Venus[48]). The temperature limits of various technology components and applications are shown in Figure 1. The general limits of commercial and military application is about 350°C and this dictates their interest in the development of the related technologies. This also shows the necessity for NASA to develop the required capabilities for missions to Mercury and Venus. Near-future potential missions to Venus are considered for operation duration of about 3 hours. For low temperatures, as on Europa and Titan, the key limiting technology is the availability of batteries that can operate at such levels.

Piezoelectric materials are capable of sustaining both very low and very high temperatures. Increasingly, new piezoelectric materials with a high Curie temperature are being developed. These materials are added to the pool of known high-temperature piezo-ceramic materials that include the single crystal $LiNbO_3$ that is known to have a Curie temperature higher than 1,100°C. Generally, actuators are readily available from commercial producers, but for planetary applications and for operation at extreme temperatures there is a great need for new capabilities. Studies at JPL's Non Destructive Evaluation and Advanced Actuators (NDEAA) Laboratory have been focused on the use of piezoelectric stacks and novel designs taking advantage of piezoelectric's potential to enable high torque/force density actuation and high electromechanical conversion efficiency. Actuators/motors that have been developed[49] are operated by various horn configurations as well as the use of pre-stress flexures that make them thermally stable while increasing their coupling efficiency. The use of monolithic designs that pre-stress the piezoelectric stack eliminates the use of the compression stress bolt. These designs enable the embedding of developed solid-state motors/actuators in any structure where the only macroscopically moving parts are the rotor or the linear translator. Finite element modeling and design tools were used to determine the requirements and operation parameters, and the results were used to simulate, design and fabricate novel actuators/motors.

[48]Bar-Cohen Y. (Ed.) (2014) High Temperature Materials and Mechanisms. CRC Press, Taylor & Francis Group, Boca Raton, Florida pp. 1-551; Bar-Cohen Y. (Ed.) (expected 2015) Low Temperature Materials and Mechanisms, CRC Press, Taylor & Francis Group, Boca Raton, Florida; Bar-Cohen, Y., Sherrit, S., Bao, X., Badescu, M., Lee, H. J., Walkemeyer, P., & Lih, S. S. (2015, April). Actuators using piezoelectric stacks and displacement enhancers. In SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring (pp. 943302-943302). International Society for Optics and Photonics.

[49]Bar-Cohen et al. (2015).

[50]Based on E. Kolawa, Solar System Exploration Technology Assessment Group (SSETAG), 2002.

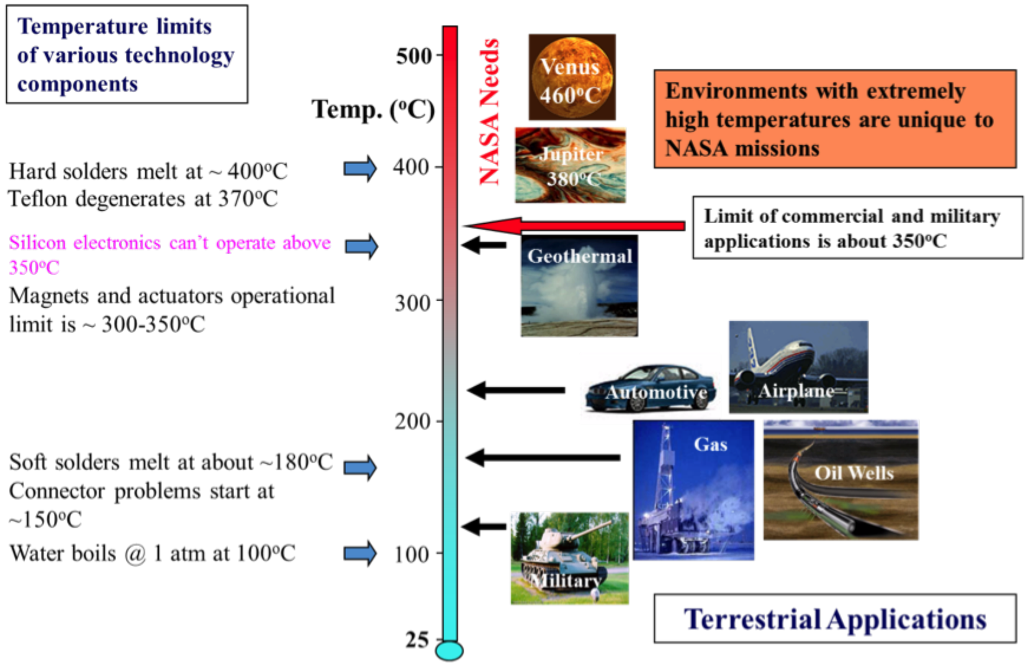


Figure 2.38: Temperature Limits of Various Technology Components and Applications.[50]

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2.5 Electro-Active Materials: Multiscale Modeling and Control

The modeling of electro-active materials (including, e.g., the diverse field of ferro- and piezoelectric ceramics and polymers) is both challenging and critical for the envisioned space technologies.

2.5.1 Challenges

Challenges arise from the *multiscale* nature of the physical phenomena, from the atomic scale all the way up to the macroscopic level. In addition, the time-dependent material response

[50] Based on E. Kolawa, Solar System Exploration Technology Assessment Group (SSETAG), 2002.

requires that the vast range of time scales—from domain switching in ceramics at atomic scales to mesoscopic polymer rheology, to the macroscopic time scales of minutes, hours, or years of structures in operation—be accounted for. Figure 2.39 schematically illustrates the length scales involved in polycrystalline ferroelectric ceramics. Furthermore, the physical problem is challenging due to the coupling of mechanical, electrical, thermal, and magnetic fields, which altogether result in the effective macroscopic material response. When operated within the piezoelectric regime,[51] that response is dominated by a linear relation between mechanical and electrical fields (e.g., between applied voltage and resulting strains during actuation, or between applied deformation and resulting voltage during energy harvesting). In actuators, this requires continuous powering of piezo-actuators. When going beyond the linear regime, complicating phenomena such as hysteresis, rate-dependence, and fatigue begin to play a role,[52] which adds to the overall modeling challenge.

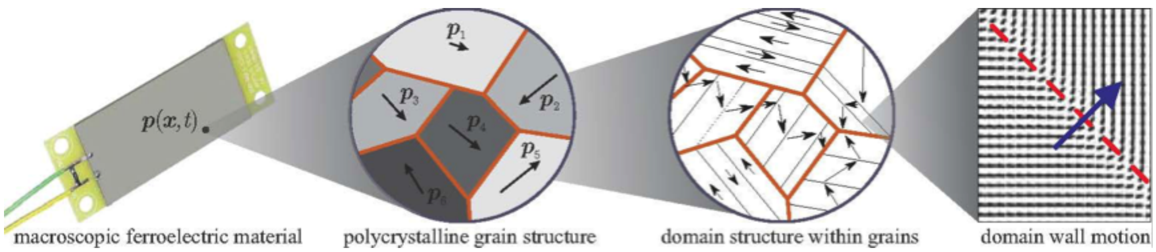

Figure 2.39: Schematic view of the length scales in ferroelectric ceramics (from left to right, i.e. from nano to macro): structure of a domain wall; domain configuration within a single crystal; polycrstyalline grain structure; and macroscopic piezo-actuator.

The importance of reliable and predictive modeling capabilities derives from the need to accurately control electro-mechanical actuators. The transformation of space systems from the launch configuration with severe space limitations into the operational final structure necessitates highly complex deployment strategies, most of which are accommodated by electro-responsive actuators. Traditional actuator solutions have made use of ferroelectric ceramics such as lead zirconate titanate (PZT), which is found, for example, in Macro-Fiber Composites (MFCs)[53] often used as actuators and sensors. By contrast, the large deformations involved during the deployment process call for electroactive polymers such as polyvinylidene difluoride (PVDF). Quite recently, flexible electronics have gained much attention for the integration of electronic circuits into large-deformation flexible materials (e.g., substrate materials including polydimethylsiloxane (PDMS), polyetheretherketone (PEEK), and hydrogels, which also possess a high mechanical

[51] Curie, J., & Curie, P. (1880). Développement, par pression, de l'électricité polaire dans les cristaux hémièdres à faces inclinées. Comptes Rendus, 91, 294-295.

[52] Wojnar, C. S., le Graverend, J. B., & Kochmann, D. M. (2014). Broadband control of the viscoelasticity of ferroelectrics via domain switching. Applied Physics Letters, 105(16), 162912.

[53] Wilkie, W. K., Bryant, R. G., High, J. W., Fox, R. L., Hellbaum, R. F., Jalink Jr, A., ... & Mirick, P. H. (2000, June). Low-cost piezocomposite actuator for structural control applications. In SPIE's 7th Annual International Symposium on Smart Structures and Materials (pp. 323-334). International Society for Optics and Photonics.

toughness and extreme extensibility.[54]) Modern alternatives have included organic and, in particular, graphene-based devices [55] at very small scales.

2.5.2 Modeling Techniques

As mentioned above, modeling techniques span a variety of scales. At the lowest scales, atomic and electronic structure calculations (molecular dynamics (MD) and density functional theory (DFT), respectively[56]) provide insight into, for example, elastic properties, piezoelectric coefficients, phase transformations (of importance in ferroelectrics near the Curie temperature), interfacial energies (for example of ferroelectric domain walls), or interaction mechanisms of material defects with domain switching in ceramics. In contrast, phase field models[57] make use of a diffusive-interface description and employ methods of continuum mechanics to describe, for example, domain wall motion and the polarization process through diffusive constitutive laws. Among other things, modeling at this scale can reveal equilibrium domain wall configurations or interactions with grain boundaries in piezoelectric ceramics such as PZT. Finally, at the macroscale, phenomenological material models[58] and associated finite-element implementations describe the underlying microstructure in an average sense and provide efficient tools to predict the performance of electro-active materials under combined electrical and mechanical loads (and possibly thermal loads). Multiscale strategies span scales, for example by passing kinetic and energetic parameters from lower to higher scales, by identifying physical mechanisms on lower scales to include in a phenomenological description at higher scales, or by combining atomic and continuum modeling into efficient coupled techniques. The former two strategies describe hierarchical multiscale methods, whereas the latter describes a concurrent multiscale technique.

2.5.3 Experiments

Experiments are of great importance to validate constitutive models and to guide the development of new modeling approaches. In particular, the challenges arising from large deformations, time dependence and hysteresis, fatigue and failure, and nonlinear actuation require experimental

[54] Li, J., Illeperuma, W. R., Suo, Z., & Vlassak, J. J. (2014). Hybrid hydrogels with extremely high stiffness and toughness. Acs Macro Letters, 3(6), 520-523.

[55] Yan, C., Cho, J. H., & Ahn, J. H. (2012). Graphene-based flexible and stretchable thin film transistors. Nanoscale, 4(16), 4870-4882.

[56] Qi, T. (2011). First-principles and Molecular Dynamics Studies of Ferroelectric Oxides: Designing New Materials for Novel Applications. PhD Thesis, University of Pennsylvania.

[57] Zhang, W., & Bhattacharya, K. (2005). A computational model of ferroelectric domains. Part I: model formulation and domain switching. Acta materialia, 53(1), 185-198; Zhang, W., & Bhattacharya, K. (2005). A computational model of ferroelectric domains. Part II: grain boundaries and defect pinning. Acta Materialia, 53(1), 199-209.

[58] Miehe, C., & Rosato, D. (2011). A rate-dependent incremental variational formulation of ferroelectricity. International Journal of Engineering Science, 49(6), 466-496.

procedures to not only assess equilibrium configurations but microstructural processes as well, in order to understand, control, and predict the material response. For instance, given the current state of an actuator, one may need to determine what voltage history should be applied in order to reach a desired final state by minimizing the power consumption and the time it takes to reach that state. As one example technique, Broadband Electromechanical Spectroscopy (BES)[59] characterizes the electro-thermo-mechanically-coupled performance of electro-active materials across wide ranges of the ambient conditions, and it has resulted in refined models to understand the highly-nonlinear behavior of PZT under large applied voltages.[60]

2.6 Control Architecture for Multi-Agent Cooperation & Interoperability

Exploration missions for robotic and autonomous systems are increasing in complexity and uncertainty with each successive mission, and even within a given mission may increase on an almost daily basis. Cooperative control algorithms have received a lot of attention in the last decade to coordinate, for instance, teams of robotic air systems (UAS) or ground robots to accomplish similar exploration missions. However, the missions demanded of these teams are increasingly dynamic, to the point that typically static centralized algorithms cannot adapt or learn in the presence of uncertainty and unforeseen changes to the mission topology, and are thus more likely to fail. Integrating intelligent control with a cooperative control algorithm offers a solution to these issues. This can be done by complementing a cooperative control algorithm, which merges local and team objectives in an efficient manner, with an intelligent control algorithm that allows a system to react to previously unencountered situations in ways that maximize objective functions. One candidate system would be a hierarchical control methodology that would provide a means to design intelligent cooperative control laws to coordinate a team of ground robot agents or rovers, with minimal or no human interaction, to respond to a changing environment while successfully accomplishing a mission in an efficient manner. Such a system entails the integration of three levels of control in a hierarchical structure:

- Low level inner-loop control via traditional proportional-integral-derivative (PID-type) feedback control
- Mid-level cooperative control
- Top-level intelligent decision-making via a Computational Intelligence (CI) method with an Executive Agent to provide onboard human expertise when needed for agent protection (loss of control) and mission efficiency.

[59] le Graverend, J. B., Wojnar, C. S., & Kochmann, D. M. (2015). Broadband Electromechanical Spectroscopy: characterizing the dynamic mechanical response of viscoelastic materials under temperature and electric field control in a vacuum environment. Journal of Materials Science, 50(10), 3656-3685.

[60] C. S. Wojnar. (2015) Exploring the kinetics of domain switching in ferroelectrics for structural applications, PhD Thesis, California Institute of Technology.

The CI agent will use both a-priori and online learning to adapt to changing rover formation configuration, environmental conditions, and mission objectives. The Executive Agent will supervise the CI agent and prevent it from commanding bad actions to the formation, as well as assist with the learning by providing expert knowledge in situations where the CI agent might have difficulty converging quickly, or at all. The Executive Agent is implemented in software and will use a knowledge base that is a representation of human experience derived from highly experienced rover operators. A hierarchical control methodology similar to the architecture for intelligent cooperative control will provide a means of designing to coordinate a team of rovers to respond to a changing and hostile environment while successfully accomplishing a mission in an efficient manner. This hierarchical control methodology will provide a means of designing intelligent cooperative control laws to coordinate a team of rovers to respond to a changing and hostile environment while successfully accomplishing a mission in an efficient manner.

Casting a cooperative control problem as a CI problem is non-trivial. Such a complex problem as coordinating multiple vehicles to accomplish a common mission presents numerous challenges to defining the components of the CI problem so that control policies are quickly and efficiently learned. Additionally, cooperative agent-based methods can lead to solutions that may be otherwise difficult to obtain, or else non-feasible. These methods are commonly characterized by a team of agents that sample and share information to generate feasible solutions to complex problems. The concepts are general in that an "agent" can represent a physical entity (like a vehicle) or a non-physical entity (like a trial solution to a design problem). Many studies have been conducted in the past decade to enable cooperative vehicle formations and cooperative search or source localization. These studies typically involved the concept of vehicle-to-vehicle artificial potential fields or formation functions based on vectored Lyapunov functions. Some studies involved simulation only, whereas others involved actual hardware demonstration of the ideas. Bellman[61] and Siljak[62] first introduced the foundations of many of these ideas. The bulk of the previous studies have focused on scenarios wherein the measured data is time-invariant and stationary. New methods are needed to address the more complicated case of time-varying, non-stationary fields.

CI learning techniques could be the missing technical piece that completes the picture. The combined CI cooperative control method would be supported by robots collecting field information through on-board sensors and sharing this information through communication networks. The robots thus represent a distributed sensor network. Each vehicle could then use the total information to autonomously determine its next control actions. Consequently, the robot controls are decentralized feedback controls. One goal would be to develop algorithms that guarantee some level of behavior stability while accomplishing the task. Learning control policies to allow multiple agents to work cooperatively toward achieving a goal is an attractive research topic with a lot of complexity. In some cases, a Reinforcement Learning (RL) approach is taken that involves

[61] Bellman, R. (1962). Vector Lyanpunov functions. SIAM Journal on Control and Optimization, 1(1), 32.
[62] Šiljak, D. D. (1978). Large-scale dynamic systems: stability and structure (Vol. 2). North Holland.

comparing the effect of using independent Q-learning algorithms on each agent in a deterministic cooperative game to using Q-learning based algorithms that involve learning joint actions between agents. Others have extended these ideas to conditions where the game is stochastic, and have tried treating the system as non-cooperative by making the individual agents unaware of each other in action selection. Considering systems where agents must coordinate but do not have knowledge of each other's actions has been an area of research deemed important for its general application to systems where agents cannot communicate with each other. Still other research has explored improving the ability of Q-learning to determine joint actions by considering mixed strategies and using Bayesian inference to estimate agents' strategies.

In most of these research scenarios, the agents are required to cooperate in games that have been abstracted such that there are no time-dependent dynamics. For control of actual multi-agent systems, this abstraction prevents feasible solutions because it is often difficult to learn control policies using RL approaches for even a single agent with time-dependent dynamics. This is especially true when dealing with heterogeneous multi-agent systems. When a multi-agent system involves agents with different dynamics, the learning process can benefit by considering some approximation of the individual dynamics. Since control of real, continuous systems using an RL learned policy requires computer-based control, it will be implemented as a sampled-data system. This is important because small adjustments to the sample time can have a large impact on the stability of the learned control policy, particularly when developed using simulation and then applied to actual hardware. Two candidate algorithms are evident. The first determines optimal sample times for sampled-data systems, and the second algorithm learns a first-order approximation for a dynamical system and uses the approximation to improve the control of heterogeneous multi-agent systems.

2.7 Tensegrity Systems

2.7.1 Information Architecture

While the isolated disciplines of materials/structures, signal processing (information architecture), and control are quite sophisticated and mature, the integration of these disciplines to obtain the optimal use of all resources is still a topic of ongoing research, and the success of complex missions will depend largely on integrating these topics at the beginning of the design rather than merely having conversations between disciplines without altering what either is doing. This Study considers techniques to integrate three different interfaces: information architecture, material architecture and control functions. In feedback control problems (such as mirror shape control), the information architecture must be chosen (i.e., which sensing functions should talk to which actuating functions, how should those sensor/actuator functions be distributed, and with what precision should they function?). A recent paper[63] provides a global (convex) solution to this problem when the system dynamics are linear, but the general nonlinear problem is still open. The criteria for the design is a set of three inequality constraints:

- bounds on total instrument cost ($, where precision increases with cost)
- bounds on control energy available (U)
- bounds on the dynamic errors allowed during control (Y).

Given these bounds ($,U,Y), Linear Matrix Inequality solutions (LMI solvers are available in Matlab) declare no solution exists for the stated performance bounds ($,U,Y), or if a solution exists, the LMI solver gives the global solution(s) to simultaneously solve for the control gains and the precisions required of all instrument functions that satisfy the constraints ($,U,Y). This algorithm shows where to spend money. By revealing the accuracy required for all sensing/actuation functions, it is clear that not all of these functions (including computational functions) need to be of high precision, and the most critical information (for the stated goals) can then be known and made with high reliability. These ideas can and should be expanded to the nonlinear setting and applied to the design of the KISS directed energy projects to find the critical performance-limiting technology (Sensing? Computing? Actuating? Control?) for that mission.

2.7.2 Material/Structure/Control Design

The second critical interdisciplinary task is to coordinate structure and control design. The structural paradigms of origami and tensegrity are the favored approaches to integrate control functions within the structure. Origami is a way to make three-dimensional structures from two-dimensional objects. Tensegrity is a way to make three-dimensional objects from one-dimensional objects. Hence tensegrity engineering can include origami features. For example, origami can suggest membrane folds that can be activated for high stiffness and control through tensegrity features and functions. Integrating the insights from tensegrity and origami can make a critical difference in performance capabilities of the directed energy project.

Minimizing mass and complexity is a recent addition to the analytical tools available for tensegrity design. For example, tensegrity structures have provided minimal mass solutions for wings, compressive structures, cantilevered structures, torsional structures, simply-supported structures, and tensile structures with stiffness constraints. Moreover, the structure that has minimal mass also has an optimal complexity (number of components), showing that structures with greater or less complexity than optimal require more mass to support the same loads. Optimal complexity has also been shown to depend upon fabrication costs, so it will be natural to penalize fabrication

[63] Li, F., de Oliveira, M. C., & Skelton, R. E. (2008). Integrating information architecture and control or estimation design. SICE Journal of Control, Measurement, and System Integration, 1(2), 120-128.

expense in the tradeoffs and optimizations.

In conclusion, a systems point of view will be required for interdisciplinary research that squeezes the performance capabilities beyond what is now available with all the sophistication of the isolated disciplines.

2.8 Multifunctional Materials with Novel Combinations of Thermal & Mechanical Properties

The space environment is among the most demanding environments in which vehicles must operate. Vehicles must travel long distances while withstanding large mechanical loads, extreme temperature swings and pressure changes, and still minimize operational costs and fuel consumption. One critical consideration in achieving these requirements is the mass of the flight vehicle, which affects every aspect of operation, such as payload capacity, range, operating cost, agility, and environmental impact. Minimizing the mass of the flight vehicle using low-density materials is thus of paramount importance.

In addition to possessing low density, any material used in a flight vehicle must also satisfy numerous other requirements, such as high elastic modulus, low thermal conductivity, and many others. Unfortunately, simultaneously realizing many of these properties in a single material can be challenging, as the fundamental physical mechanisms that determine each property are often linked. As an example, consider a material required for a thermal protection system on a space vehicle. This material should possess low density, low thermal conductivity, and high elastic modulus. However, because thermal conductivity and elastic modulus increase together in typical solids, low thermal conductivity materials often have poor mechanical integrity. A classic example of such a material is the ceramic thermal protection tiles used for the space shuttle, which were thermally insulating but were so fragile that they could be damaged even by rain droplets.

More generally, in aerospace applications there is a frequent need for materials with the contradictory combination of ultralow density and thermal conductivity yet high elastic modulus. The availability of such materials could have a transformative effect on aerospace and space exploration via applications such as ultralight thermal protection systems, structural thermal insulation, and low thermal conductivity structural elements.

At present, however, materials with the required properties do not exist. Materials with sufficiently low thermal conductivity have poor mechanical integrity, while sufficiently stiff materials have high thermal conductivity. The physical reason that this combination of properties is difficult to achieve is that the thermal conductivity and Young's modulus are inherently linked to the strength of the interatomic bond joining the atoms of a solid.

Thus, in most materials, achieving certain combinations of material properties is challenging. However, recent advances in fabrication techniques have enabled the creation of materials in which certain properties are due to the architecture of the material rather than the composition and microstructure, as in traditional materials.[64] These fabrication methods thus offer the intriguing possibility that previously impossible property combinations can be realized in a single material.

As an example, consider ultralight nanolattices, which are periodic, three-dimensional, cellular materials with solid fractions of around 1%.[65] In these structures, the mechanical properties are due not only to the constituent material but also to the lattice architecture, in exactly the same way that the strength of a bridge is due to both the steel used and the design of the trusses.[66] However, the thermal conductivity of the lattice remains low due to the atomic and nanoscale structure and is relatively unaffected by the specific lattice structure. Therefore, in these lattices the Young's modulus and thermal conductivity are largely decoupled. Furthermore, as the structure is approximately 99% air, it also possesses ultralow density and is thus capable of fulfilling all three material requirements described at the beginning of this section.

A key distinction exists between nanolattices and lattices with larger unit cell size. In the latter case, the effective properties are well described by classical theories. In contrast, the critical dimensions of nanolattices are only tens of nanometers. At these small length scales, the thermal properties of solids may be very different from those of the constituent materials. For example, the effective thermal conductivities of crystalline materials may be orders of magnitude smaller than the bulk value due to classical size effects, in which interfaces and boundaries scatter energy carriers.[67]

Nanolattices thus offer an additional design variable compared to macroscopic lattices—the minimum feature size—and can achieve a wider range of properties through careful engineering of classical size effects.

While the mechanical properties of nanolattices are under investigation, no experimental or computational studies of thermal transport in nanolattices have been reported, to our best knowledge. As a result, our understanding of the thermal properties of these structures is very limited. The motivation for this work is thus to fill in this fundamental knowledge gap and thereby extend the functionality of nanolattices to the thermal domain. Fundamental questions we seek to answer are:

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[64] Schaedler, T. A., Jacobsen, A. J., Torrents, A., Sorensen, A. E., Lian, J., Greer, J. R., ... & Carter, W. B. (2011). Ultralight metallic microlattices. Science, 334(6058), 962-965.

[65] Jang, D., Meza, L. R., Greer, F., & Greer, J. R. (2013). Fabrication and deformation of three-dimensional hollow ceramic nanostructures. Nature materials, 12(10), 893-898.

[66] Meza, L. R., Das, S., & Greer, J. R. (2014). Strong, lightweight, and recoverable three-dimensional ceramic nanolattices. Science, 345(6202), 1322-1326.

[67] Cahill, D. G., Braun, P. V., Chen, G., Clarke, D. R., Fan, S., Goodson, K. E., ... & Shi, L. (2014). Nanoscale thermal transport. II. 2003–2012. Applied Physics Reviews, 1(1), 011305.

- How do geometrical parameters like truss thickness, nodal connectivity, and lattice architecture affect the thermal conductivity?
- How are the different energy carriers, phonons and electrons, affected by atomistic and nanoscale defects in the structure?
- How can thermal conductivity be tuned by engineering classical size effects over a hierarchy of length scales?

These questions are difficult to answer due to experimental and fabrication challenges. Our work is able to gain these insights by applying experimental and computational capabilities samples created using unique fabrication tools at Caltech.

2.9 MEMS for Energy Harvesting in Extreme Environments

Miniature devices are attractive options for adaptable space structures because of the reduced size, power, and mass advantage they offer. A variety of possible components that can make up a deployable system domain are shown in Figure 2.40. The main subsystems–including engineered materials, miniature instruments, electronics, sensors, power/energy storage systems, and actuators–all encompass a collection of interacting components and sub-components that make up miniature devices.

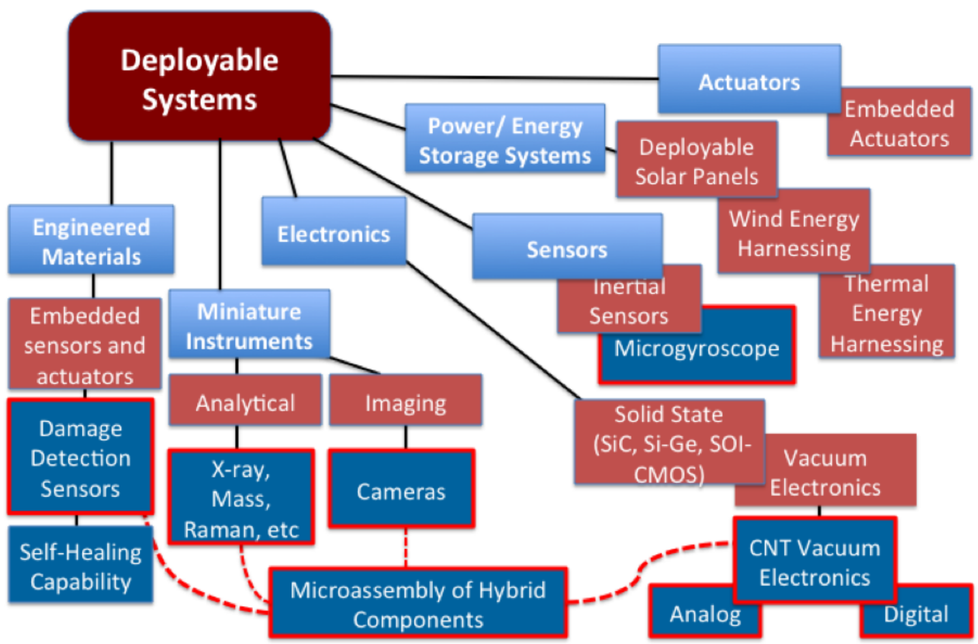
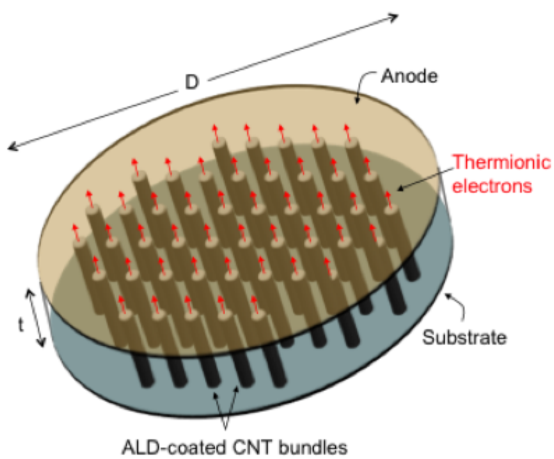


Figure 2.40: Schematic showing overall system components and their interrelations of a deployable system.

Such miniature devices normally consume power in the range of tens of microwatts to several milliwatts, depending on their functionality and duty cycle of operation. This power range, while easily accommodated by batteries, requires a long-term strategy for continuous sourcing when prolonged operation is desired. Especially for adaptable space structures, supporting systems should be self-sufficient, multifunctional, vibration tolerant, and reliable or maintenance free. For miniature systems, the power levels involved are in the range of what is possible to harvest from extreme environment surroundings using micro-electro-mechanical systems (MEMS). This report explores some potential strategies for energy harvesting using MEMS in extreme environments.

2.9.1 Harvesting Heat Energy

This technique is useful in high-temperature environments. A device designed such that a small temperature difference is achieved between two of its electrodes produces thermoelectricity. Thermoelectric generators are known to produce higher power compared to piezoelectric generators. A thermoelectric power cell using low work function metal coatings on arrays of nanostructured (to achieve high surface area) cathodes can be used to generate electricity at low applied voltages and the cells themselves can be conformally integrated with large area space structures. The electricity production is a combination of thermionic and field emission phenomena as long as the anode is thermally connected to a sink to ensure some temperature difference between the two electrodes.



- Exploit large surface area of nanofiber/nanotube substrates.
- Coat nanofibers conformally with low ϕ metals (eg., K = 2.4 eV)

Figure 2.41: Concept sketch of a Thermionic Power Cell for heat energy harvesting along with calculated current density possible for different emission materials.

2.9.2 Harvesting Vibration Energy

Mechanical vibration is an expected aspect of space structures. The vibration energy can be harvested using piezoelectric, electromagnetic, and electrostatic transduction. Through careful material selection, the extreme environment applicability is ensured. The first two approaches are suitable for energy harvesting in extreme environments.

In piezoelectric structures, applied stress is converted to electrical energy. Common MEMS structures used here are cantilevers. Cantilevers coated with piezoelectric material produce oscillatory electricity proportional to the vibration-induced strain. The magnitude of electric signal produced by one MEMS cantilever is small, and hence an array of cantilevers is employed to amplify the electricity to usable levels. Silicon carbide cantilever structures with aluminum nitride piezoelectric coatings have been studied for energy harvesting at high temperatures.

In the electromagnetic approach, vibration is coupled to the core of an induction coil in the presence of magnetic field similar to a "dynamo." In a MEMS structure, permanent magnets can be electroplated using Permalloy. All of this can be enclosed inside a protective package that is resistant to extreme environments.

2.10 3D Printing to Fabricate Geometrically-Complex Reconfigurable Cellular Structures

The next generation of manufacturing technology required to fabricate multi-material cellular structure will require complete spatial control of material and functionality as these structures are created layer-by-layer to provide fully customizable, high-value, multifunctional geometries with embedded capabilities. With contemporary Additive Manufacturing (AM, also known more popularly as 3D printing) providing the base fabrication process, a comprehensive manufacturing suite will be integrated seamlessly to include:

- extrusion of a wide variety of robust thermoplastics / metals
- micromachining
- laser ablation
- embedding of wires and fine-pitch meshes submerged within the thermoplastics
- micro-dispensing
- robotic component placement

Collectively, the integrated technologies will fabricate multi-material structures through the integration of multiple integrated manufacturing systems (multi-technology) to provide multi-functional products (e.g., where an antenna in the structure can also serve to strengthen the structure mechanically, thus serving more than one function).

The use of 3D printing to make unique electronics in complex geometric forms has been demonstrated in the past by UTEP, as shown in Figure 2.42, using conductive inks as interconnects

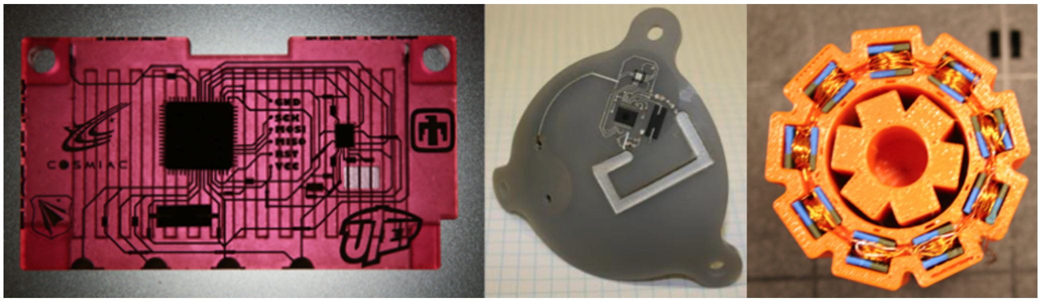


Figure 2.42: Preliminary examples of parts made using Multi-material Additive Manufacturing including (a) a sensor system to be launched in to Low Earth Orbit in late 2013 in a UNM CubeSat, (b) a helmet insert with wireless acceleration detection system—both of which were fabricated with stereolithography substrates and conductive ink traces. The final picture (c) is a motor in-process with thermoplastic, magnets and wires.

(Figures 2.42(a)(b)).[68] While inks are improving, limits to curing temperatures have resulted in relatively poor performance in terms of conductivity and current carrying capacity, which is required for high frequency and high power applications. Recent advances in embedding thermal wires within thermoplastic substrates have provided printed circuit board (PCB)-like routing densities/performance (Figure 2.43(a)) with final connections to electrical components enabled by laser welding (Figure 2.43(b)). Moreover, embedded fine-pitch wire meshes can serve as either ground planes or patch antennas as shown in Figures 2.43(c) and (d). These meshes provide two additional benefits: volumetric reduction of the structure and enhancement of the mechanical properties of the overall structure. By introducing meshes robustly within the polymer, novel attachment points can be created between polymer and metal components within larger systems to robustly join subsystems of disparate materials (e.g., welding polymers to metal structures). Furthermore, wires can be printed in coils within the cell structure to

[68] Cahill, D. G., Braun, P. V., Chen, G., Clarke, D. R., Fan, S., Goodson, K. E., ... & Shi, L. (2014). Nanoscale thermal transport. II. 2003–2012. Applied Physics Reviews, 1(1), 011305; Joe Lopes, A., MacDonald, E., & Wicker, R. B. (2012). Integrating stereolithography and direct print technologies for 3D structural electronics fabrication. Rapid Prototyping Journal, 18(2), 129-143; Roberson, D. A., Wicker, R. B., & MacDonald, E. (2012). Microstructural characterization of electrically failed conductive traces printed from Ag nanoparticle inks. Materials Letters, 76, 51-54; DeNava, E., Navarrete, M., Lopes, A., Alawneh, M., Contreras, M., Muse, D., ... & Wicker, R. (2008). Three-dimensional off-axis component placement and routing for electronics integration using solid freeform fabrication. In Solid Freeform Fabrication Symposium, The University of Texas at Austin, Austin TX, Aug (pp. 4-6); Navarrete, M., Lopes, A., Acuna, J., Estrada, R., MacDonald, E., Palmer, J., & Wicker, R. (2007). Integrated layered manufacturing of a novel wireless motion sensor system with GPS. Texas University at El Paso with W. M. Keck Center for 3D Innovation; Mireles, J., Kim, H. C., Lee, I. H., Espalin, D., Medina, F., MacDonald, E., & Wicker, R. (2013). Development of a fused deposition modeling system for low melting temperature metal alloys. Journal of Electronic Packaging, 135(1), 011008; Wicker, R. B., MacDonald, E., Medina, F., Espalin, D., & Muse, D. W. (2012). U.S. Patent Application 13/343,651; Wicker, R. B., Medina, F., MacDonald, E., Muse, D. W., & Espalin, D. (2013). U.S. Patent Application 13/829,723.; Wicker, R. B., Medina, F., MacDonald, E., Muse, D. W., & Espalin, D. (2013). U.S. Patent Application 13/829,921.

provide embedded electromagnets to connect cells without consuming volume required for the load bearing walls of the structure. Figures 2.43(g) and (h) illustrates printed coils in which thermal management has been incorporated. Minimized versions of these coils could be placed just beneath each of the external surfaces in a cellular structure to provide an attraction force between cells, one of many examples of how this manufacturing technology can enable new devices and structures never before possible.

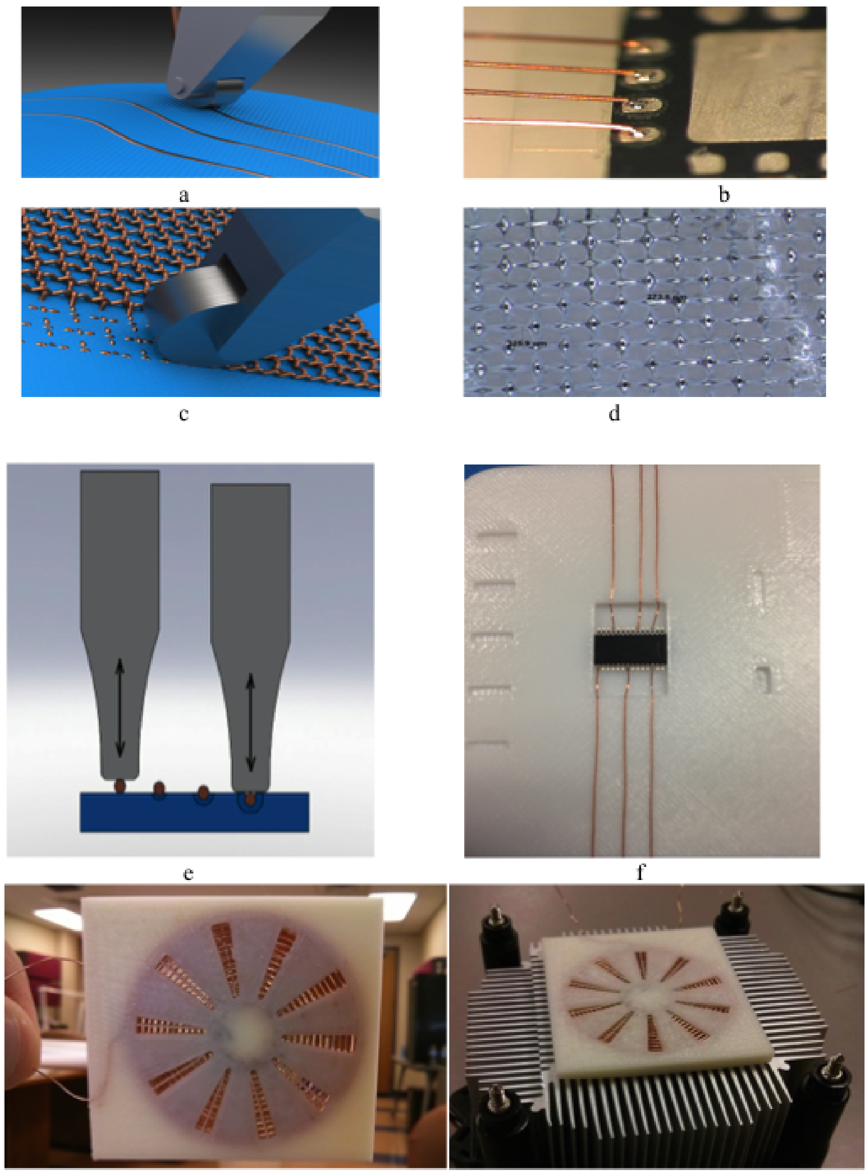


Figure 2.43: (a) CAD depiction of wire embedding, (b) laser welded component, (c) CAD depiction of embedded mesh and (d) picture of surface after mesh embedding, (e) Embedding horn in process, and (f) Embedded wires attached to surface mount component, (g) a 3D Printed coil, and (h) coil with heat exchanger.

2.11 Integrating Antennas & Rectennas with Solar Panels for RF Harvesting & Wireless Communications

For this Study, we target the implementation of multifunction and reconfigurable energy harvesters as a novel technology to achieve higher efficiencies of energy harvested and lower costs in renewable energy systems. These next-generation energy harvesters will be capable of using multiple renewable energy sources and will also be able to make decisions based on availability of said sources to optimally harvest energy. Current state-of-the-art energy harvesting devices utilize one or two modes of energy, such as: solar only, RF, or thermal. It is feasible to combine more than 3 energy-harvesting functionalities in one device, namely: photovoltaic (PV), thermovoltaic, and radio frequency (RF). A simplified schematic of such an energy harvester is shown in Figure 2.44.

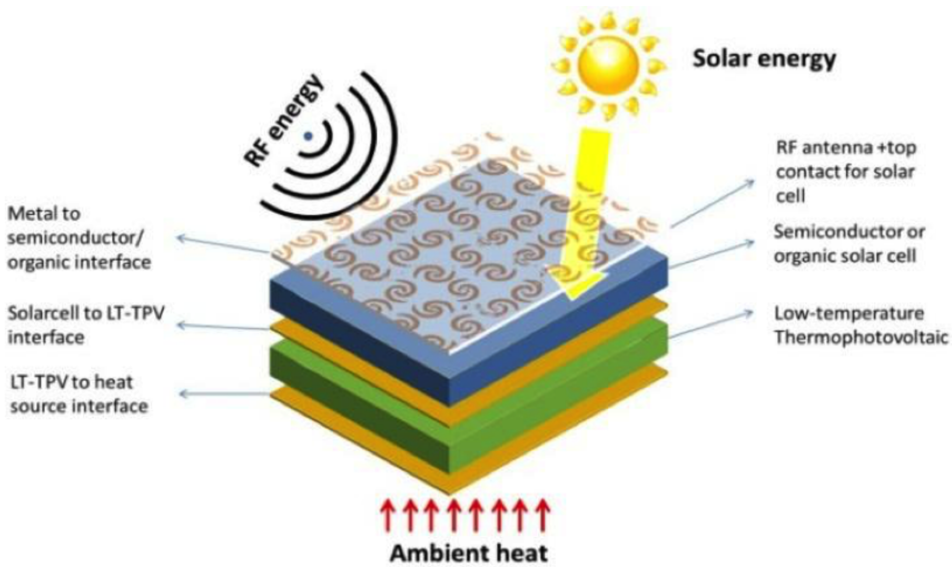


Figure 2.44: Schematic illustration of an energy-harvesting device.

Broadband Antennas for Harvesting RF Energy

A multitude of ambient RF sources exist at different frequencies that are constantly radiating power in all directions, creating a rich scattering environment that can be harvested as an energy source. Our aim has been to capture this ambient RF energy, along with solar energy, and convert it into DC (direct current) power that either can be stored in a battery or used to feed power into existing electrical infrastructure. This power can also be used to operate an antenna for communication purposes. The basic idea is to use an antenna within any frequency band of interest. The variation of the RF power density depends on both frequency and time. The DC power which can be harvested depends on the available RF power (P_{RF}) and conversion efficiency (η_{conv}) from RF to DC: $P_{DC} = \eta_{conv} P_{RF}$.

The choice of the antenna and how well the antenna is matched to the rectifier are very critical in optimizing harvested energy from the incident ambient RF wave. A basic architecture of a rectenna (rectifying antenna) is shown in Figure 2.45.

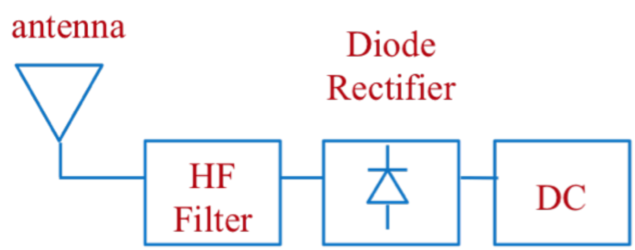


Figure 2.45: Basic rectenna architecture.

We propose to use the spiral antenna shown in Figure 2.46(a) due to of its advantageous wideband properties (shown in Figure 2.46(b)), which will allow us to harvest RF energy over a wide frequency range. Other antenna configurations can also be used. The antenna must be matched to a rectifier and the dimensions of the spiral antenna must be optimized to achieve maximum DC power. Once the single rectenna unit is optimized, then an array of these spiral antennas can be used to harvest energy over the entire surface of the combined solar/antenna device, as shown in Figure 2.44.

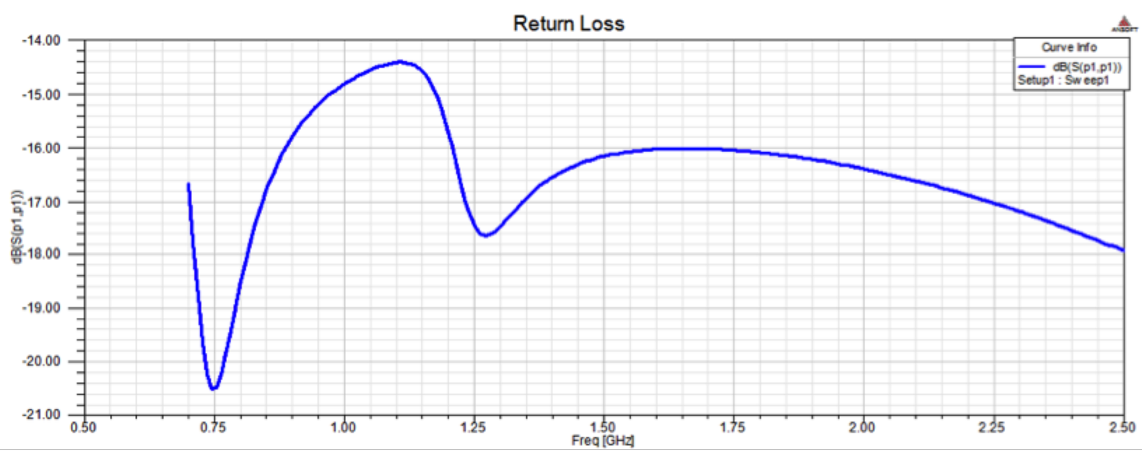


Figure 2.46: (a) Spiral rectenna (b) its Ultra wideband S11 characteristic.

The next innovative step is to use the antennas during solar photovoltaic operation as top, and possibly, bottom contacts to the solar cell units. Such an approach will both use less precious metal material (one pattern is used for both RF antenna and PV contacts), as well as gain an antenna without giving up surface area (hence, without sacrificing solar cell external efficiency).

Figure 2.47 shows an example of a broadband antenna (PIFA, Planar Inverted F Antenna), made of copper tape on top of a solar panel.

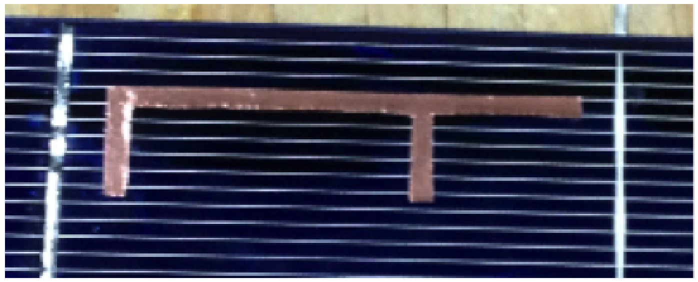


Figure 2.47: An example of an antenna (PIFA) design cut from copper tape for solar cell integration.

A different approach is to design a transparent antenna for RF harvesting that is integrated with a solar panel. The proposed integration does not affect the solar cell light absorption. The antenna is completely transparent and can be optimized to maximize RF to DC conversion without affecting the solar panel efficiency.

Some of the embedded antennas can be used as communication antennas from title to tile. These antennas can be powered by the energy stored by the rectennas already embedded on the same tile. The difference between the two types of antennas is that the recifying antennas are connected to a rectifying diode in their input, whereas the communicating antenna will be connected to a simple receiving/transmitting circuit that will also be embedded in the same tile as the rest of the antennas in the solar panel.

The size of the wireless communication system will be designed based on the actual frequency of operation. The overall objective is to maximize the power transferred to the system for storage while still being to operate effectively using the corresponding communication system.

2.12 Smart Tiles: Building Blocks for the Colonization of the Solar System

This Study investigated the potential of multifunctional space structures for climate control, scientific experiments, autonomy, and power generation in space, on planets, and in extreme environments. The workshop participants represent a diverse and respected cross section of industry, government, and academic organizations and interests, and this document represents the culmination of discussions, brainstorming and practical ideas to create long-term, sustainable, non-nuclear capabilities for colonization and power generation efforts throughout the solar system. An emerging concept identified in the Study was that of the Smart Tile. The Keck Institute for Space Studies' Smart Tiles represent the foundation of an energy infrastructure for the solar system and the beginning of a swarm intelligence for the moons and planets.

Over the past decade, wide interest has developed into the potential colonization of the Moon and Mars. NASA along with several commercial interests, with SpaceX being the most prominent, have invested significant capital into the development of rockets and capsules with the payload capacity and technical capability to move not only equipment and resources but also human passengers to these far away destinations.

While having the capability to reach these asteroids, planets, and orbits is necessary, rockets and capsules are not enough to sustain a human colonial effort in space. In order to have a long-term, sustainable environment, human colonists must have certain elements—building blocks—that will keep the colonists alive, keep their equipment operational, and alleviate costs of the missions. The contents of this Study provide such an infrastructure and include solutions to not only the power generation and resource harvesting technologies necessary but also the type of verifiable, robust software backbone needed to ensure safe operation, fault tolerance, and alleviate bad emergent behaviors in the remoteness of space. Additionally, this Study highlights the community outreach and scientific merits of the technologies proposed.

The uniqueness of the results of this Study lie primarily in the low-cost, distributed nature of its products. The Smart Tile, as discussed here, is a generic, multifunctional piece of hardware that can be fitted with various physical augmentations for power generation, scientific experiments, resource gathering, locomotion and communication.

The specific contributions of the Smart Tile to colonial space efforts are the following:

- **Multifunctional, semi-autonomous software and hardware.** The Smart Tile platform supports heterogeneous, multi-generational hardware and software components that will collaborate, potentially with human feedback, to accomplish mission objectives. A Smart Tile can be a uniform or non-uniform shape, with any type of equipment present, so long as it has the basic physical or software capabilities for interacting with other Smart Tile equipment or agents, through wireless or wired interfaces.

- **Power generation.** The standard Smart Tile is cubic, hexagonal or thin-squared and has at least one side covered in a solar panel oriented toward the sun, when available. Smart Tiles are also composed of material and apparatus necessary to effect thermo-electric power generation based on temperature differences between surfaces of the tile. This thermo-electric power generation capability provides the tiles with the feature of generating electrical currents to connected equipment, even if no solar source is available. A separately discussed power generation capability could come from the absorption and utilization of ambient radiation.

- **Communication.** The Smart Tile provides wired and wireless interfaces for communicating with other equipment over short ranges. Through standard, exposed interfaces, the Smart Tile can attach itself to long range communication equipment for beaming information to an orbiter, Earth, or some other information source or sink.

- **Resource gathering.** The Smart Tile is connected to other Smart Tile equipment through standard interfaces to facilitate the gathering of resources such as oxygen and hydrogen from ice formations, as those found on Mars within the first few feet of top soil, with other Smart Tile-enabled hydrolysis equipment. Other mining operations are possible for asteroid or planetary resource utilization.

- **Locomotion.** The Smart Tile can be equipped with augmentations for locomotion, as appropriate to mission and environment. These locomotion capabilities include wheels for surface-based locations, ion-beam thrusters for space maneuvers, inflatables for rolling, or various other possibilities. Locomotion can also be accomplished via symbiotic relationships with other Smart Tile-enabled rovers or other autonomous entities capable of physically moving the tile into place.

- **Distributed control and verification.** The Smart Tile is expected to be deployed en masse and connected together, potentially over large geographic regions. Due to the remoteness of their operation, degrees of autonomy are exposed. For the purpose of verifiability of group intelligence, we expect Smart Tile structures and collaborative groupings to use synchronous models of computation that can be formally verified with software model checking or statistical model checking, as appropriate. This will ensure collision-free, safe movements and operation.

- **Autonomous Space Structures.** The Smart Tiles provide permanent magnets to fasten themselves to equipment or other Smart Tiles in preprogrammed structures that may be free-floating in space or affixed in position on a terrestrial body. The creation of these structures can be verified, using formal methods and statistical model checking, to prevent collisions and ensure safe construction. The function of structures could be additional protection from the elements for colonists, solar arrays for power generation, or even the creation of large antennae arrays if the Smart Tile has the appropriate facing for such reception and beaming.

- **Power beaming.** Smart Tiles share power with connected equipment and antennae arrays that can beam power wirelessly across vast distances. Because the Smart Tiles are constantly generating power, they are ideal sources of beamed energy using microwaves or various other wireless transfer possibilities.

- **Computational offload.** Smart Tiles contain processors, memory, and other computational elements that may be useful for computational offload by colonists. Additionally, Smart Tiles may create ad-hoc, cloud-like data centers that provide standard interfaces for authorized organizations or personnel to perform local, potentially life-saving, computations for mission needs.

- **Localization.** Smart Tiles can be outfitted with localization equipment to aid incoming craft with information about local debris fields, hazardous areas, refueling stations, and exact locations of craft in the area, based on any number of localization systems—whether centered on Earth or translated to coordinate systems of nearby planets, planetoids, or other fixed or relative systems.

- **Scientific Merit.** Smart Tiles can be enhanced with sensors for barometric pressure, radiological ambience, seismic sensors, chemical sensors, visual and infrared sensors, wind gauges, and other scientific equipment to provide data for study. Because these tiles communicate together, the data can be aggregated and processed locally before sending results to scientists on Earth or in the colony for further analysis.

- **Community Outreach.** Any colonial endeavor requires public attention and outreach to remain relevant to the public on Earth. Such outreach can ensure that support and funding for the colonization continues throughout the duration of the intended mission. This Study outlines such community outreach, such as allowing remote participants to issue commands, across the vastness of space, directing the Smart Tiles to construct preprogrammed structures on Mars or in space, or to spell out the name of an organization using thermal or light signatures that can be detected back on Earth.

- **Low cost.** The standard Smart Tile can be mass-produced and is relatively small and light weight. This allows for the deployment of thousands of tiles in a single mission. The result for NASA should be incredible impact and utility for a relatively low financial footprint, especially when compared with deploying larger, more monolithic payloads. Attached to this low cost is a platform that is extensible, verifiable, and capable of handling legacy interactions, potentially over decades.

Our Study found significant scientific and financial value in the concept of the Smart Tile. Not only does it provide an infrastructure for NASA explorers to establish long-term colonies on other planets, asteroids or moons, but the Smart Tile also enables power generation and resource sharing for commercial interests, such as those seen in the SpaceX Dragon Capsule roadmaps. Any colonist or space-faring company will need power, oxygen, hydrogen, communication infrastructure, localization, and other features provided by Smart Tiles. However, without significant investment in this type of infrastructure, any colonial or long term space enterprise will be far more dangerous, costly, and prone to failure.

Smart Tiles can power projects in a variety of settings, including low-Earth orbit, the Moon, Mars, Venus, small bodies, and icy bodies. They can also power space-based industrial and scientific projects, from cubesats, commercial satellites, and bio-reactors, to directed-evolution stem cell generators, 3-D printers, and high-end fiber optic extruders. Significantly, Smart Tiles can power the hydrolysis units that will stockpile and pre-position rocket fuel, breathable oxygen,

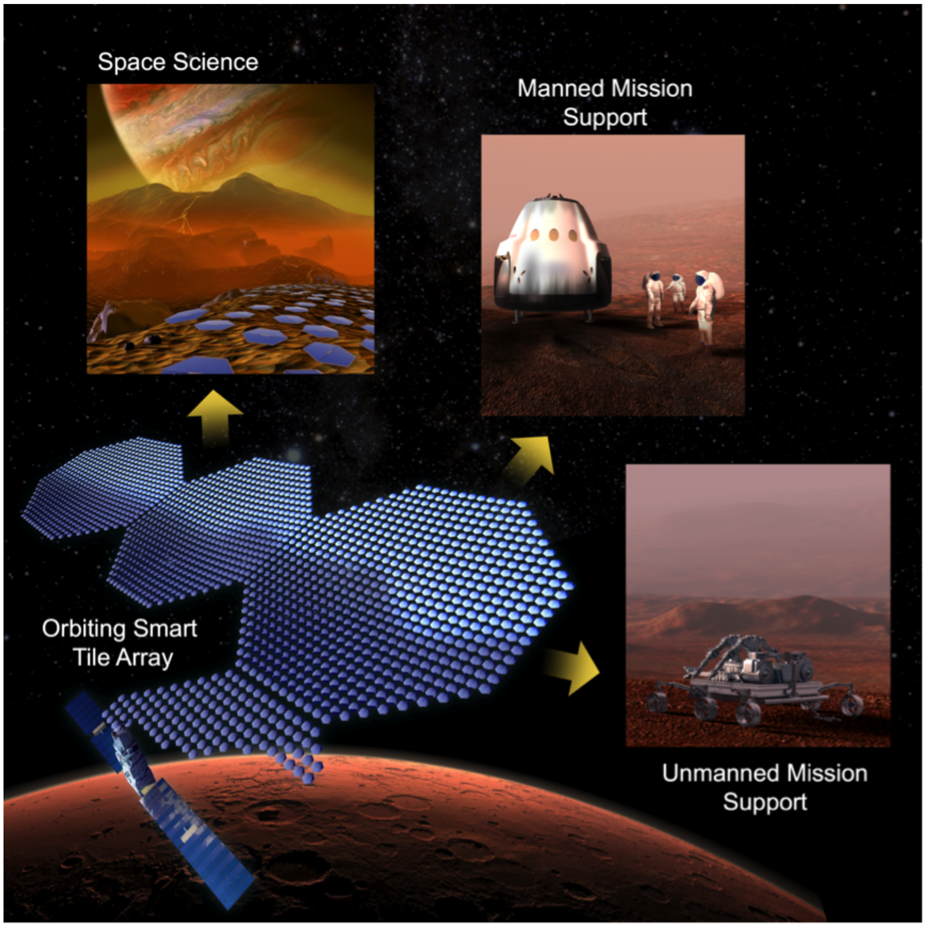


Figure 2.48: Examples of the many uses of Smart Tiles. Art: Chuck Carter

and drinkable water on the Moon, Mars, and in fuel depots in space. In addition, they can provide positioning services, seismic monitoring, atmospheric measurement, visual imaging, cloud computing, and artificial-intelligence-driven data analysis throughout the solar system. Smart Tiles offer the beginning of a swarm intelligence for the moons and the planets. They provide a novel opportunity for massively parallel processing planetary missions.

2.12.1 Summary of Recommendations

The Study concluded with the following recommendations:

- **Build a roadmap toward strategic Smart Tile deployment.** The Study participants recommend a three-tiered deployment of Smart Tile structures.
  - First, the formation of a structure, such as a solar panel, with a dozen or more Smart Tiles in geosynchronous orbit. These tiles would be self-locomoting via short bursts from ion-beam thrusters.

  – Second, the formation of a Smart Tile structure on a nearby body, such as the Moon. This second deployment may not be a test but the start of a real Moon colonial site. This second deployment should test out most of the features expected to be used on a potential Mars site.
  – Third, a major deployment of at least one thousand tiles on Mars, potentially spread across a large geographic region. If multiple deliveries are possible, the capabilities of the tile set could be staggered to provide energy and communication infrastructure along with a small number of scientific tiles (e.g., with barometric pressure and wind gauges). Other missions could deliver more specialized equipment that may be useful to colonists. Using cost estimates and capacities of vehicles such as the Dragon Capsule for SpaceX, we expect to deliver between 1,300 to 1,600 Smart Tiles per mission, with each tile potentially offering unique scientific measurements and insight into the environment and potential of colonization efforts in the area.

- **Establish a focused solar system colonization community.** An ecosystem is needed to foster the development of core concepts of not only the Smart Tiles and the technology needed but also the business and community outreach for financial incentives and scientific merits and possibilities of colonial efforts. Smart Tiles may be able to facilitate mining operations in asteroids, scientific experiments across the solar system, and even refueling of space-faring vessels via harvesting of water-ice or other oxygen and hydrogen packed locations

- **Develop technologies and infrastructure to mass-produce Smart Tiles.** Study participants have interacted with various companies and organizations interested in the deployment and use of the Smart Tiles. However, even for a single mission filling the payload capacity of a Dragon space capsule, a mass-production capability is desired.

- **Develop a roadmap for sharing resources with companies.** With capabilities such as power beaming and computational offload, other organizations and businesses will be willing to pay for excess power and computation made available via Smart Tile clusters in space, on the Moon, or at Mars. A roadmap should be constructed that details to these entities when services would be available, the financial transfer necessary for such services, and the detailed process for acquiring resources.

2.12.2 Tile Characteristics and Interactions

In this section, we highlight the software and physical capabilities of the Tile, focusing on the communication and collaboration components required to accomplish mission objectives. The software architecture as described in this section is embedded into computing layers within each smart tile, as shown in Figure 2.50. The tile can be almost any depth and have many sides. However, throughout this section, we will discuss a cubic tile with symmetric side lengths.

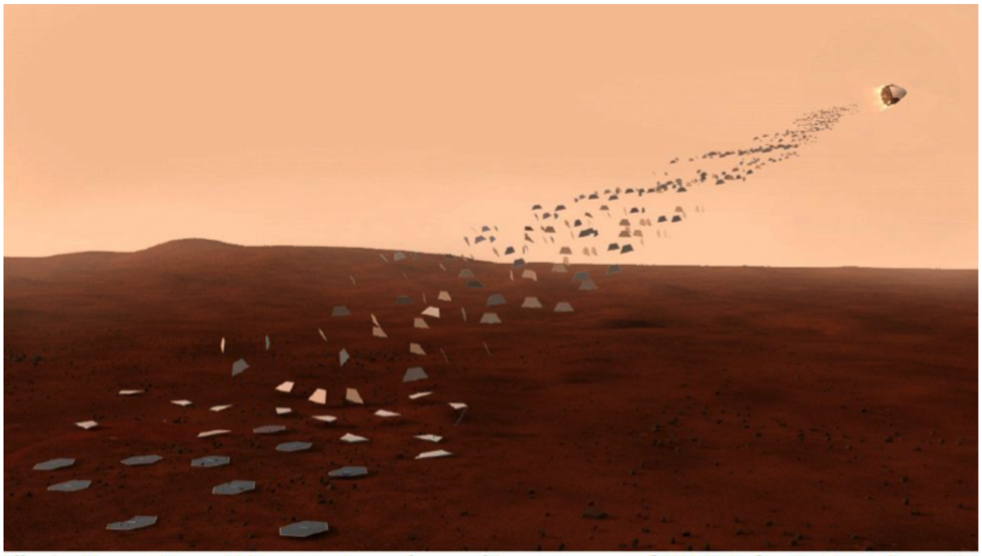


Figure 2.49: Artist's rendering of a SpaceX Red Dragon capsule dropping Smart Tiles on the Martian surface. Art: Anna Nesterova.

2.12.3 Tile Networking

The Networking ID 1 (Simple Communication) is one of two options of potential interfaces. The first option would be a physical network contact that is meant for one sender and one receiver. In this first option, each tile would have two physical networking contacts, one for sending data and the other for receiving data. These contact points would likely be strips, rather than points, as tiles must be able to stack and connect to each other in a way that is not necessarily linear (linear stacking would only allow us to form straight lines and most useful structures would require tiles to be overlapping and jagged). The second option would be a bidirectional contact strip that allows for connected tiles to send and receive information across the strip (as a serial or UDP port is generally setup). Preference would be for serial or UDP support over this medium. An example strip configuration is shown in Figure 2.51.

Table 2.5: Networking Mediums.

ID	Transport Type	Wired	Each Side	Receivers	Senders
1	Unidirectional	Yes	Yes	1 or 2	1 or 2
2	Shared	Yes	Yes	All	All
3	Radio	No	No	All	All

The Networking ID 2 (Shared Communication) is a shared bus that allows for fast, efficient group communication with physically connected tile structures. Ideally, this networking option would use an open standard like IP Multicasts or Broadcast to provide for stable, well-tested communication

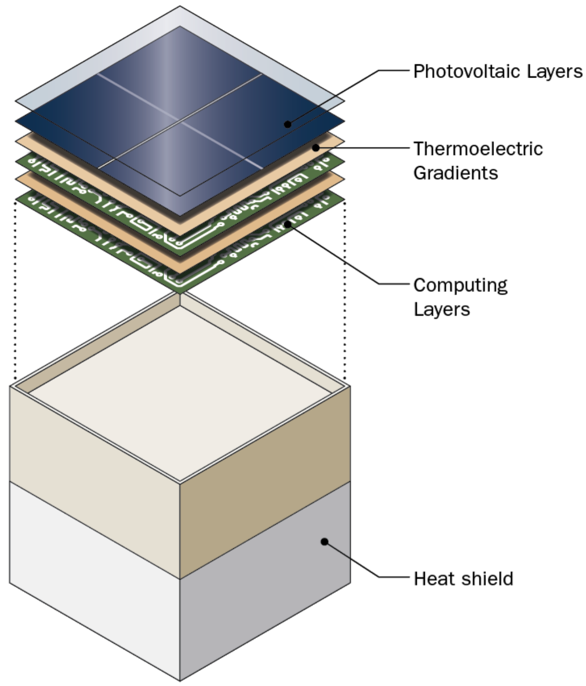


Figure 2.50: Layering of Computing Layers within the Tile. These computing layers will support the software architecture for discovery, communication, and control of tile structures.

mechanisms. Like Networking ID 1 (Simple Communication), the Shared Communication contact is likely best implemented as a contact strip to allow for offset tile structures (rather than only being useful in linear stacking). An example multicast strip configuration is shown in Figure 2.52.

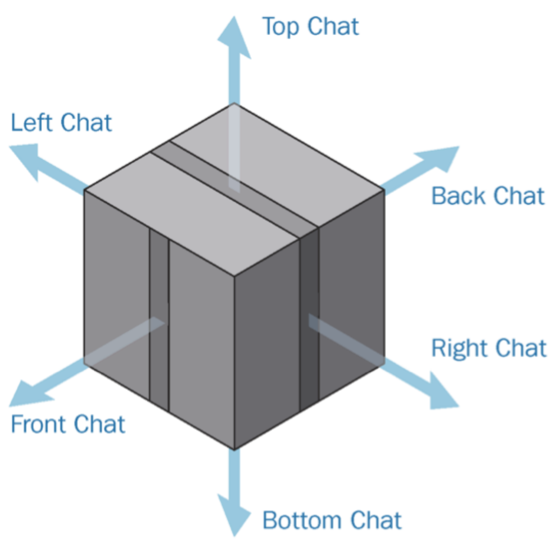


Figure 2.51: Example strip configuration for Simple Communication paradigm (Network ID 1).

Networking ID 3 (Radio Communication) is a shared wireless medium that is best utilized by tiles communicating their readiness or intent to join an existing tile grouping or some other mission-related information (such as the need for additional tiles for a mission-related structure).

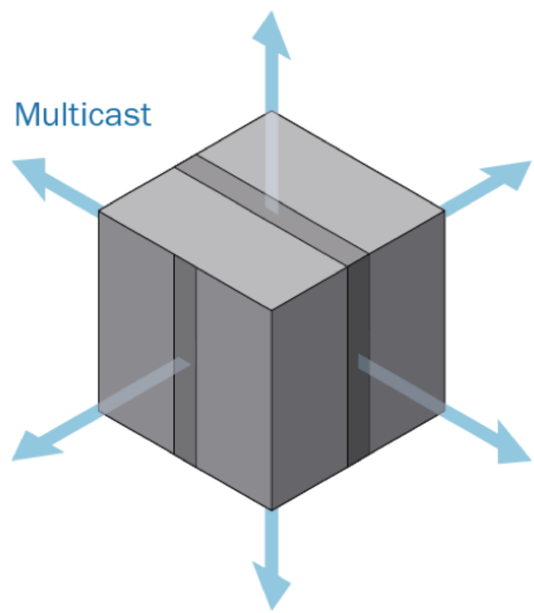


Figure 2.52: Example strip configuration for Shared Communication paradigm (Network ID 2).

2.12.4 Tile Collaboration

Collaboration can take many forms and may involve physical contact with other tiles but is not necessarily limited to physical interactions. Communication is expected to take place before and during any type of collaborative tile activity.

Tile Collaboration Activities

Collaborative activities amongst tiles may include but are not limited to the following:

- Negotiations for computational resources
- Negotiations for structural, physical joins
- Negotiations for team-based computations or learning systems

Figure 2.53: Radio broadcast is likely best done with an internal antennas to prevent exposure to elements.

Tile Collaboration Standards, Tools, and Practices

Collaboration requires standards for interacting between Tiles. The minimum necessary standards for Tile Collaborations are the following:

- Standard communication protocol (Challenge 1)
- Standard interfaces for adding/removing/controlling physical actuators for moving tiles into place and physical collaborations between tiles (Challenge 2)
- Standard method for constructing algorithms and new platforms for working within a Tile Operating System and Environment (Challenge 3)
- Standard methodology for verifying appropriate Tile behaviors for common Tile Collaborations such as building structures (Challenge 4)

For the purposes of Section 2.12.2, a Tile Operating System (TOS) is a software operating system that is likely to require real-time support (soft real-time or hard real-time) to guarantee timing and control properties required of the Tile Operating Environment. The Tile Operating Environment (TOE) is the complete cyber-physical system that is monitored, manipulated, and controlled by the TOS. The TOE consists of the sensors, actuators, computing components, processors, memory, etc. of the Tile. The TOS is the base operating system that provides access to software APIs for access and control of the TOE.

Atop the TOS will be a layered middleware system that facilitates virtual and physical collaboration activities between Tiles. There are several candidate middleware systems possible, but we will base our description specifically on the open sourced Group Autonomy for Mobile Systems (GAMS) [0] and Multi-Agent Distributed Adaptive Resource Allocation (MADARA) [0, 0, 0, 0] projects at CMU. These middlewares can provide the following features that will prove useful for a Tile collaboration system:

- Algorithm interface and abstraction
- Platform interface and abstraction
- Support for heterogeneous hardware, processing and software
- Communication interface and abstraction that is tolerant to disconnects
- Portable and quality-of-service-enabled threading, timing and control
- Group autonomy verification tools and languages (e.g. Model Checking for Distributed Algorithms (MCDA/DASL) [0, 0, 0] and Distributed Adaptive Real-Time (DART/DMPL) [0] projects)
- Discovery of tiles, software agents, and other participants in the physical or computational subsystems

The GAMS/MADARA middleware combinations address the standards challenges within the Tile Collaboration context in the following ways:

- MADARA provides a fault-tolerant communication standard implementation using UDP-based protocols for unicast, multicast, and broadcast which may be directly used for the networking requirements expressed in Section 2.12.1. As part of this Study, we also implemented a serial transport interface for use with MADARA, which may prove useful for Simple Communication paradigms (Network Transport ID 1). MADARA helps satisfy Challenge 1, expressed earlier in this section.
- GAMS is built atop of MADARA, and provides an algorithm and platform abstraction for adding new Tile structures, platforms and coordination algorithms. The MADARA infrastructure is robust and portable, currently allowing for usage of C++, Python and even Java applications and has ports for Intel and ARM processors. GAMS consequently provides the pieces necessary for the informal standards outlined in Challenge 2 and 3 of this section.
- Because GAMS and MADARA have unique quality-of-service and guaranteed properties related to timing and control of distributed agents, tools exist for verification of group behaviors constructed with GAMS and MADARA. Collaborative behaviors based on

Synchronous Models of Computation (SMOC) (generally implemented via global clock or synchronized barriers) have been formally verified for MADARA-based programs in the MCDA project. The verification tools in place help to address Challenge 4. This is an active research area and additional verification tools and methodologies may be necessary to fully accomplish verification of a fully asynchronous model of computation (AMOC) based Tile Collaboration system.

- Because GAMS and MADARA support passive discovery mechanisms via filtering, described in more detail in Section 2.12.3, Challenge 7 can be inherently solved via these middleware layers, as long as communication is possible between tiles, preferably using the communication mediums outlined in Section 2.12.1.

2.12.5 Tile Collaboration Discovery

For tiles to collaborate, they must be able to detect each other's presence. Otherwise, tiles could only work together if they had knowledge of other tiles' existence at deployment time (e.g., when launched from a mothership) and a guarantee that other tiles known at deployment would never fail. As part of the objectives of a tile-based self-building structure, such constraints are impractical, especially given the likelihood of hardware failures and transience of tiles coming in and out of the system over time.

With MADARA, discovery of tiles can be passively done at runtime via filters in MADARA. Filters are user-defined callbacks that are invoked during sending, receiving, or rebroadcasting over a network by the MADARA middleware layer. Filters are provided with several contextual fields that aid in discovery, and these contextual fields are outlined in Table 2.6.

For discovery, only two methods are necessary from the above within a filter to codify a discovery process in MADARA: 1) get_originator and 2) get_current_time. Together, these fields define who is sending knowledge and what time the filter is being called to establish a heartbeat between each tile. Given a reasonable hertz rate of regular knowledge updates from each tile—e.g., 1hz of knowledge over any networking interface—each tile can passively discover who is in communication range, who is directly connected, and even where the connection is affixed on the tile surface.

To monitor active versus inactive tiles, a small data structure such as a string to a 64 bit integer map (e.g., in C++ std::map <std::string, uint64_t>) can be used to keep track of the originator to last message received time mapping. The tile then uses the difference between the last seen message time from the originator and the current time to determine if the connection to the other tile is lost, using an arbitrarily defined disconnected threshold value (e.g., 20 seconds since last communication received from a tile).

Table 2.6: MADARA Contextual Methods for Filters.

Method	Description
add_record	Adds a named record to the next stage of filtering.
clear_records	Clears any records previously added to filtering.
get_current_time	Returns current time stamp in seconds.
get_domain	Gets the networking domain.
get_message_time	Returns time stamp of sender creating message.
get_operation	Returns type of operation currently being processed. This can be IDLE_OPERATION, SENDING_OPERATION, RECEIVING_OPERATION, or REBROADCASTING_OPERATION.
get_originator	Returns unique identifier of sender.
get_receive_bandwidth	Returns the total bandwidth usage in bytes/s over last 10s.
get_send_bandwidth	Returns the bandwidth usage used for sending by this process in bytes/s over the last 10s.

Once the disconnected threshold is violated, the tile can either remove from the collaboration list or it can simply not be counted in an aggregation counter that checks for stale collaborator tiles. The latter would simply require any algorithm to count the number of participating tiles against the disconnected threshold by iterating through the list of known originators and their last received message. This is a straight-forward, automatable task.

As part of the discovery process, it is likely in the best interests of tiles to inform their neighbors of any useful sensors and actuators. For instance, self-locomotion mechanisms like ion beam thrusters can be very useful for an existing tile structure to take advantage of for increasing overall thrust for the structure. A tile with a robotic arm accessory may be useful for arranging tiles that are not self-locomoted or for stabilizing two parallel structures (whether tile-based or not). Additionally, because tiles can be various sizes and depths, the discovery protocol should also take note of these tile dimensions as some surfaces may have no connector types, no communication types, or may have actuators (e.g., foldable arms) that should not be affixed to by other tiles, unless no other tiles are present.

2.12.6 Tile Functionalities

It is expected that each tile will have specialties and capabilities in regards to sensing, actuation, power generation, locomotion, and networking. Some tiles may only have wireless communication and none of the Simple or Shared Communication transports in Section 2.12.1. Tiles may have no locomotion mechanisms at all and may instead be embedded in space-age fabrics or picked up and moved by a ground-based rover into final positions. We summarize some of the more interesting platform possibilities discussed in the workshops in Tables 2.7 and 2.8.

Table 2.7: Locomotion Mechanisms.

Type	Environments	Dependencies	Self-Powered
None	Any	Arm-enabled external agent	No
Ion-beam thruster	Space	Battery and/or power generation	Yes
Wheels	Surfaces	Battery and/or power generation	Yes
Flywheels	Surfaces	Gravity, battery and/or power generation	Yes
Magnets	Space or surfaces	Variable, type of magnet, power needs	Yes
Foldable arm	Space or surfaces	Battery and/or power generation	Yes

The software architecture is designed with the concept of a Platform class that extends from a base class. This base class has stub methods for utilizing locomotion (see Table 2.7) and physical connections to other tiles (see Table 2.8). As noted in the above tables, some of these locomotion and connection mechanisms are dependent on other tiles negotiating for services and connections.

For locomotion, we can assume one of two main variants: 1) no locomotion and 2) self-powered locomotion. A tile with no locomotion capabilities essentially serves as a building block or conduit for other more specialized tiles. It must be either manufactured into a preset configuration or moved by an arm-enabled tile, rover, ship, or other agent in the system.

Table 2.8: Physical Connection Mechanisms for Stability.

Type	Environmen	Dependencies	Negotiation Types
Magnets	Any	Variable	Feel, no comms
Clasps	Any	Gravity, surface moisture	Feel, reservation, auction
Tether	Any	Surface moisture, corrosion	Reservation, auction
Fixed	Any	Manufacturing process	None
Foldable arm	Any	Surface moisture, corrosion, grip strength	Reservation, auction

A self-powered movable tile may use one of many types of locomotion capabilities. On surfaces of astronomical bodies, other tiles or vehicles, tiles may use wheels, internal flywheels, or magnetic forces. The software architecture would simply need to be setup, per tile, with the capabilities of the tile along with a type of localization system based off touch, laser positioning or some other system. In space, the tile may be provided with some type of booster, ion-beam, or laser

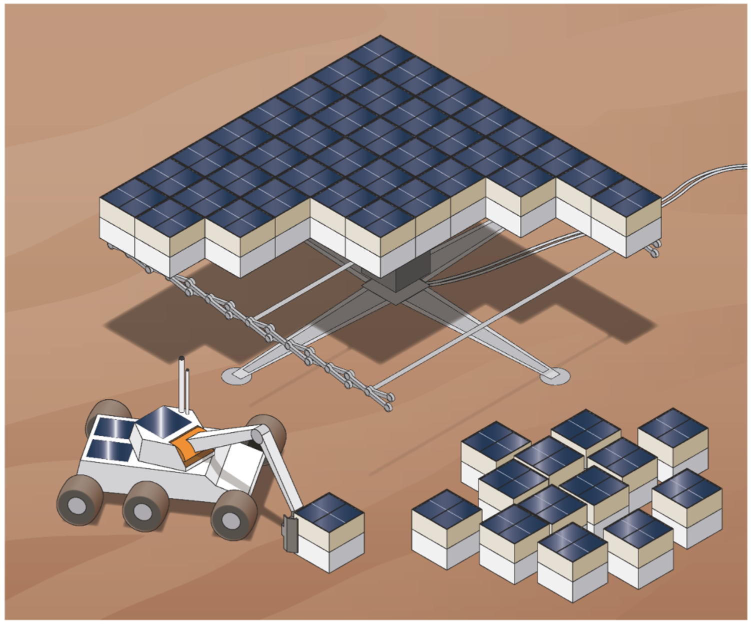


Figure 2.54: Static tile structures can be moved and affixed into place using an arm-enabled robotic system.

thruster on at least one tile surface to allow it to jet forward into space. As with other locomotion mechanisms, in order to move into position with other tiles, localization is important—not only for moving across terrestrial or empty space but also across a structure for balancing, power needs, or whatever the mission needs. Figures 2.56 and 2.57 show examples of tiles traversing, via self-locomotion, a larger structure and between structures as part of a space mission context. Figures 2.54 and 2.55 show examples of heterogeneous, non-ambulatory tile sets being aided by arm- and wheel-enabled robotic helpers to move into position on a ground-based or elevated power station on a terrestrial surface, e.g., Mars.

Physical connections between tiles are important for stabilization of a tile-based structure. Without physical connections that bind tiles together, tiles are unlikely to be able to maintain a shape or structure. This is especially problematic in space, where a lack of physical connection can result in fluctuating structures that drift apart and collide. Physical connections may also provide power, which may be especially useful for long standing tile-based structures to be repowered by retiling missions.

This power sharing feature of physical connections may be useful for using existing dead tile structures for communication (e.g. using a powerless tile structure as a communication bridge between two still operational tile structures by binding to the dead tile structure and using its wireless capabilities). Figure 2.58 shows such a dead tile structure being actively engaged and used for communication or power sharing between two active, functional tile structures.

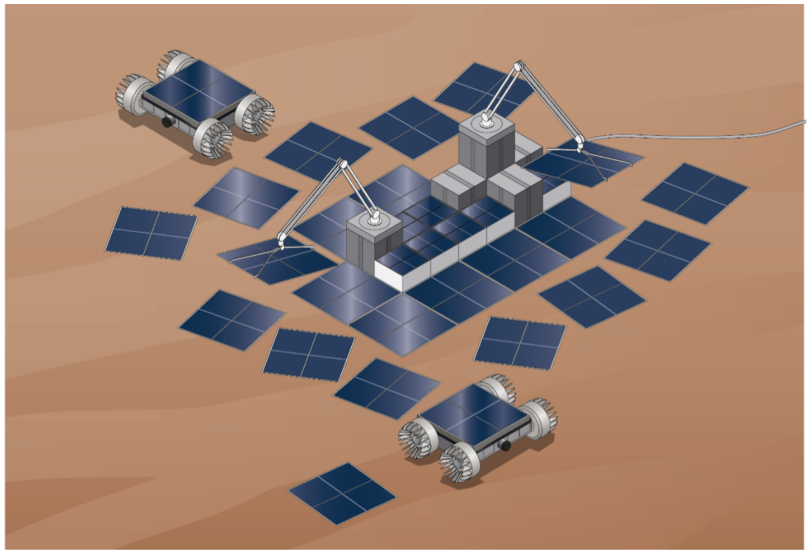


Figure 2.55: Constructing a power station or other structure with robotic arm-enabled tiles and small, battery-powered rovers from a heterogeneous tile set.

Table 2.8 shows potential connection mechanisms for tile stability. Permanent magnets and fixed tile bindings may be the most universally applicable to surface and space environments. A fixed tile binding is intended to be a manufactured fixture, either as part of the design process in factories or potentially in space with 3D-printed polymers of some cohesive material, usually to prevent disconnections and floating out of useful range. Other binding possibilities include simple clasp mechanisms and line tethering.

For a software architecture, such as the one we propose with GAMS, the platform simply needs to be aware of the physical connection capabilities of the tile along with any negotiation process required for establishing a position directly connected to a neighboring tile.[69]

[69] Chaki, S., & Edmondson, J. (2014). Model-Driven Verifying Compilation of Synchronous Distributed Applications. In Model-Driven Engineering Languages and Systems (pp. 201-217). Springer International Publishing; Chaki, S., & Edmondson, J. (2014, July). Toward parameterized verification of synchronous distributed applications. In Proceedings of the 2014 International SPIN Symposium on Model Checking of Software (pp. 109-112). ACM; DART Modeling and Programming Language project page: https://github.com/cps-sei/dmplc. May 11, 2015; Edmondson, J., & Schmidt, D. (2010). Multi-agent distributed adaptive resource allocation (MADARA). International Journal of Communication Networks and Distributed Systems, 5(3), 229-245; Edmondson, J., Gokhale, A., & Neema, S. (2011, December). Automating testing of service-oriented mobile applications with distributed knowledge and reasoning. In Service-Oriented Computing and Applications (SOCA), 2011 IEEE International Conference on (pp. 1-4). IEEE; Edmondson, J., & Gokhale, A. (2011). Design of a scalable reasoning engine for distributed, real-time and embedded systems. In Knowledge Science, Engineering and Management (pp. 221-232). Springer Berlin Heidelberg; Group Autonomy for Mobile Systems project page: https://github.com/jredmondson/gams. May 8, 2015; Model Checking for Distributed Algorithms project page: https://github.com/cps-sei/mcda. May 8, 2015; Multi-Agent Distributed Adaptive Resource Allocation project page: http://madara.sourceforge.net. May 8, 2015.

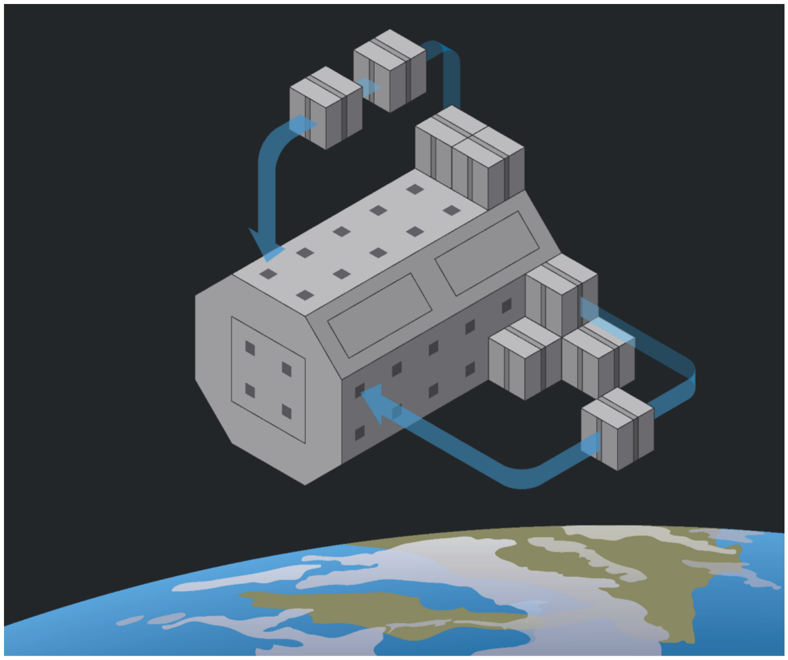


Figure 2.56: Active movement of tiles across an existing structure to increase surface area, e.g., for solar arrays.

Additional advantages of the Smart Tile concept include:

- Support for the scientific goals of NASA's Decadal Surveys:
  - Networks of Smart Tile seismic detectors can gather planetary science data on the Moon, Mars, Titan, Europa, Venus, or on the Martian moons Phobos and Deimos.
  - Smart Tiles can provide power, visual sensors, chemical sensors, and radio sensors to upcoming small body, comet, and icy body missions (Figure 2.59). For example, if Smart Tiles had been included on the ESA's Rosetta mission, the Philae comet lander would never have experienced either a power problem or a communications difficulty.
  - Rovers on Mars or the Moon could recharge their batteries from the power supply stored by Smart Tiles, as well as receive weather reports on upcoming destinations from Smart Tiles scattered across the lunar and Martian surface.
  - Climate observation and atmospheric research can be done via chemical, visual, temperature, barometric pressure, and humidity sensors on Mars, Venus, Titan, and Europa.
  - Smart Tiles could provide power, communications backup, and cloud computing for a sample return from the south pole of the Moon.

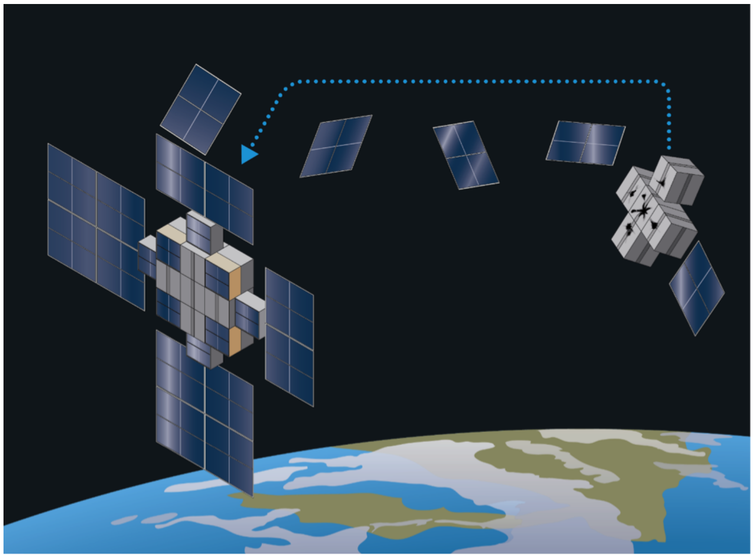


Figure 2.57: Disabled satellite structure transferring self-locomoted heterogeneous tiles to create larger solar array structure.

  - Smart Tiles can be used on the icy surface of Titan or Europa to provide energy, computing power, communications, and sensor data.
  - Smart Tile arrays in low-Earth orbit and in deep space could power satellites hunting for incoming asteroids.
  - Smart Tiles could contribute power, communications, and brainpower to missions designed to sample comets.
  - Temperature hardened Smart Tiles could provide seismic information and atmospheric data on Venus.

- Potential support for other partnerships:
  - The United States military is interested in protecting assets from anti-satellite weapons, which could easily damage a single large satellite. Networks of Smart Tiles are not vulnerable to attack in this way.
  - Harvesting solar energy in space has enormous potential to minimize the human carbon footprint, as evidenced by investments and endorsements from the Chinese Academy of Space Technology, the Japan Aerospace Exploration Agency (JAXA), Mitsubishi, and Northrop Grumman. Smart Tiles can form massive solar arrays for minimal cost and gather energy from ambient radio waves and heat differentials in addition to traditional solar energy collection.

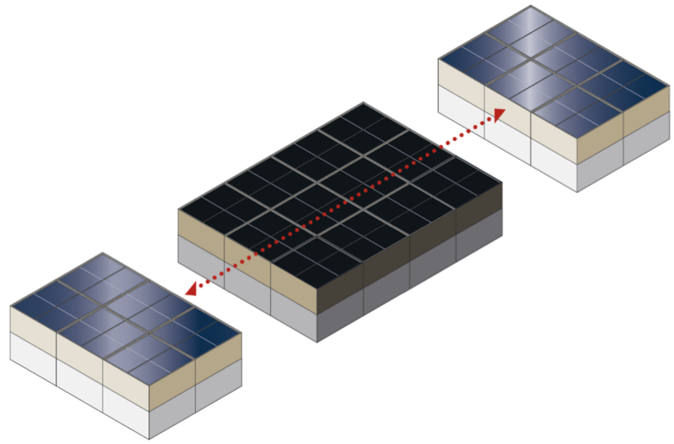


Figure 2.58: Two active tile structures harness the communication of a dead tile structure (shown as black) for communication between the blue active tile structures.

- In conflict zones, Smart Tiles may be a useful alternative power source to gasoline. Ordinary gas can cost between $200 to $400 a gallon to deliver in a battle zone, and its delivery contributes to more fatalities than just about any other mission. Smart Tiles can transmit energy to high-tension areas directly from space.
- Supplying power in emergencies—from earthquakes to tsunamis—is expensive and slow. Smart Tiles could be used beam electricity to these disaster sites directly.
- Power supplied by Smart Tile solar arrays in earth orbit can contribute to state-mandated renewable energy goals (e.g., California and Washington).
- Smart Tiles can provide power, positioning, and computing services to asteroid mining companies, such as Peter Diamandis' Planetary Resources and Rick Tumlinson's Deep Space Industries.
- Smart Tiles can provide useful power and cloud computing capabilities to the International Space Station.
- Power from Smart Tiles can be beamed to cubesats, commercial projects, and scientific experiments parked in the vicinity of the ISS, as proposed in XISP's space-to-space power beaming project.
- Industrial experimenters and processors, such as Made in Space and manufacturers of high-cost, specialized fiber optic cables, are can take advantage of the zero-gravity environment of space, and Smart Tiles can provide power for these industrial users.
- The oxygen, hydrogen, and liquid water electrolyzed using Smart Tile power can supply fuel depots in space, supporting a permanent space transportation infrastructure.

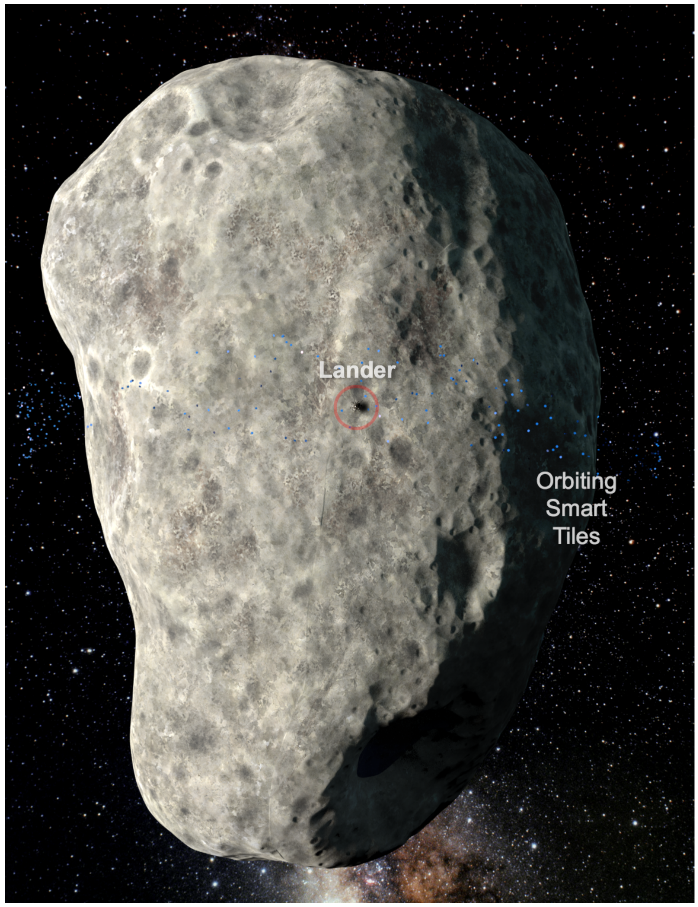


Figure 2.59: Artist's rendering of orbiting Smart Tiles collaborating with a lander. Smart Tiles could have fail-safed the Rosetta Mission to Comet 67P/Churyumov-Gerasimenko, providing power, communications, and computational power to the Philae probe despite the presence of cliffs and shadows. Art: Chuck Carter

In summary, the Smart Tile is what the brick was to the ancient Babylonians. The Babylonians used bricks by the millions to build something new: cities. The Smart Tile is a generic, inexpensive, multifunctional piece of hardware designed to be deployed by the thousands and tens of thousands to provide an infrastructure for planetary exploration. The Smart Tile is designed to provide the basic building block and the backbone of life's expansion into space.

3. The Path Forward

3.1 Possible Mission Scenarios

Possible mission scenarios include:

- Orbiting solar concentrator beaming power to receiver on rover
- Fabric-sat with multiple nodes
- Hybrid solutions for energy harvesting: transparent PV film + thermoelectric, JPL power tile, spike-in-ground solution
- Reconfigurable antenna on flexible substrate

Another possible mission scenario emerged at the conclusion of the second workshop in which Mars or the lunar environment (e.g., atmosphere, day-night cycle) were possible targets. In this scenario, multiple cubesats could be ejected gradually during long terminal descent. The Tiles survive reentry, then break apart and distribute on surface as nodes of energy infrastructure.

TheTiles we envision would have the following features:

- PV surface transparent to IR light
- reconfigurable printable antenna for comm
- printable circuit with high subsystem integration
- heat storage unit
- spike with heat pipe emplaced in the ground (on the Moon or Mars, where there is a sufficient thermal gradient inside the soil to be used for thermoelectric generation.

In contract, the JPL Tile (developed as a result of a past DARPA-funded effort), has the following features:

- Integrate bar-shaped power management and distribution with thin film
- 7x9x2 cm
- 46 grams
- Li-Ion battery
- Inside its own polymeric packaging
- Deployable, foldable, stackable, flexible
- Modular, envisioned as 24 modules.
- One-to-one match between footprint of solar cells and battery
- 720 Wh for 3 kg
- With 1 m deep heat pipe, on Mars can get Watts, mWatts on Moon

The objective of the proposed Tile is then to create a self-contained node design and use as many nodes as needed for infrastructure (energy recharging stations, triangulation network of beacons for surface navigation). Possible uses of these tiles include: sensory purpose, power management, communications Wifi network to communicate among tiles, if they are physically connected (wire) can do power and communication simultaneously, but not benefit of scale. A large computing power (ARM-Cortex processor $<$ 10 microW/mHz) would be available at each node.

3.2 Possible Maturation Path

A proposed maturation path, depicted in Figure 3.1, would include:

- Unit node testing in ground
- Unit node testing in relevant environment
- Multiple nodes testing in ground
- Multiple nodes testing in relevant environments
- Other hybrid solutions (unit node + solar)
- Test of locomotion solutions (rover docking on port)

- Tests of highly integrated sheets of tiles

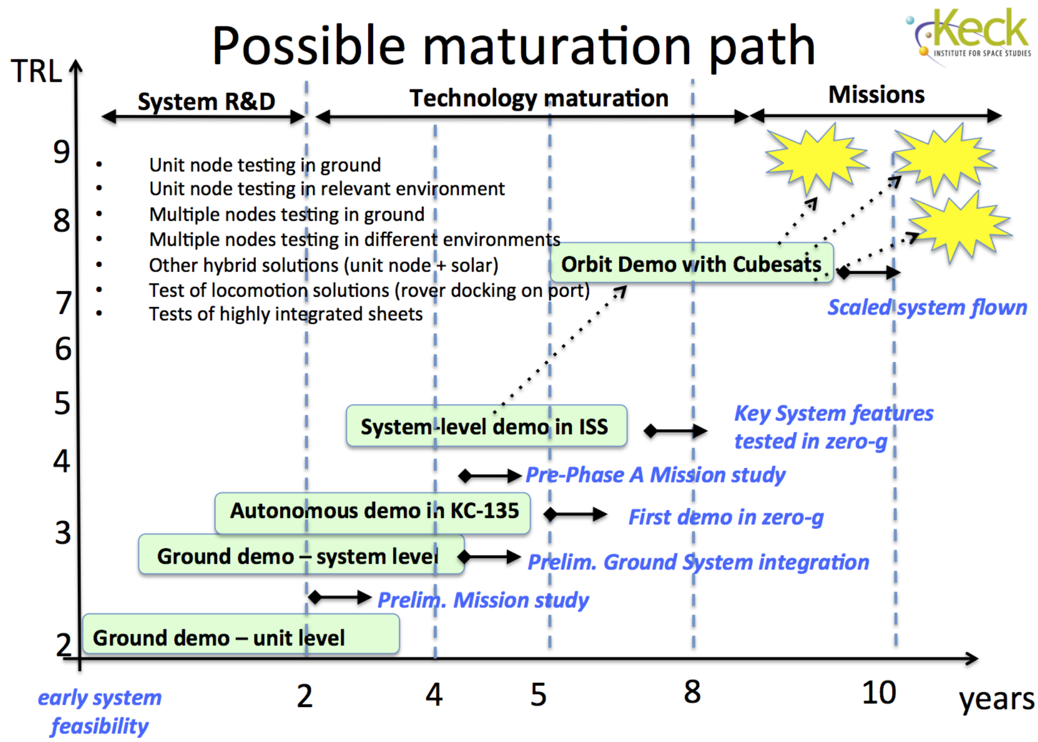


Figure 3.1: Proposed maturation path for the concepts described in this report.

3.3 A Vision for Energy-projecting Multi-functional Systems across the Solar System

This report has offered a range of new technologies for Energy-projecting Multi-functional Systems (EPMFS) for applications across the Solar System. EPMFS could be the start of an energy infrastructure for the solar system. They could power projects in Low Earth Orbit, on the Moon, on Mars, on Venus, on moons from Europa and Titan to Phobos, and on Small Body, Icy Body, comet, and asteroid missions. EPMFS could also power space-based industrial and scientific projects from cubesats, commercial satellites, and bio-reactors, to directed-evolution stem cell generators, 3-D printers, and high-end fiber optic extruders. Most important, EPMFS could power the hydrolysis units that will stockpile and pre-position rocket fuel, breathable oxygen, and drinkable water on the Moon, Mars, and in fuel depots in space. EPMFS would provide the opportunity for the first massively parallel processing planetary missions in history. In addition, EPMFS could provide positioning services, seismic monitoring, atmospheric measurement, visual imaging, cloud computing, and artificial-intelligence-driven data analysis throughout the solar system. EPMFS would offer the beginning of a swarm intelligence for the moons and the planets. Furthermore, EPMFS would help lift the eyes of STEM students to the skies.

The SpaceX Dragon capsule is one possible vehicle that could carry EPMFS to Mars. See Figure 3.2.

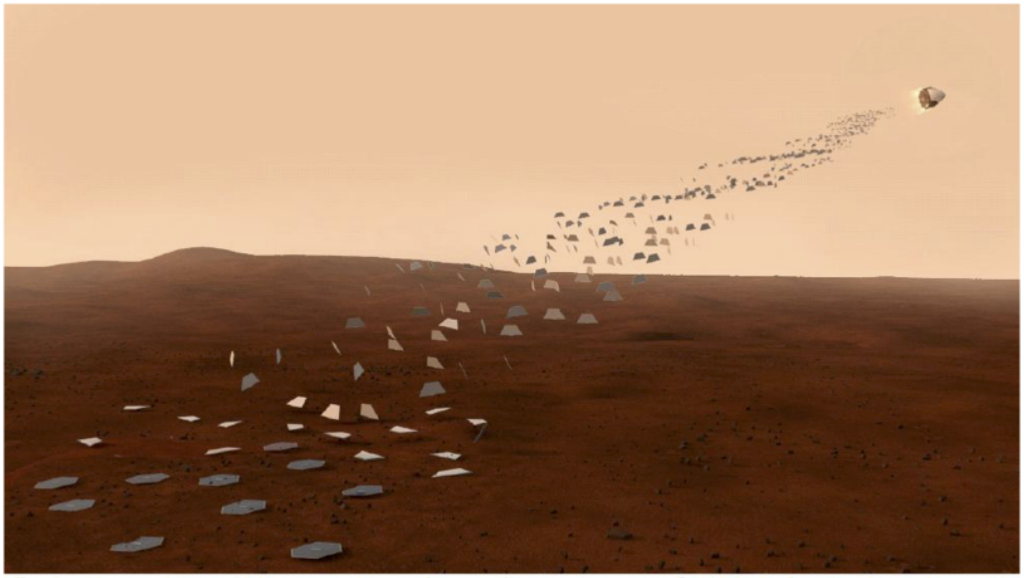


Figure 3.2: A SpaceX Red Dragon capsule dropping large numbers of EPMFS tiles on the Martian surface. Art: Anna Nesterova.

One of the concepts discussed in the Keck Institute Study was that of the EPMFS Tile. As a network of tiles, EPMFS tiles would be a scalable system, with embedded functions of great advantage for an energy infrastructure. EPMFS could also establish energy and information beachheads on the Moon, on Venus, and on the moons of Jupiter and Saturn for a fraction of traditional NASA costs. Normally, NASA missions are based on one-of-a-kind machines manufactured by hand. That makes traditional NASA technology expensive. For example, the Curiosity Mars Rover cost $2.5 billion just to build. It is a brilliant machine, but an expensive one. EPMFS take another approach. They are modular units that can benefit from mass production and economies of scale. In other words, EPMFS can be inexpensive. Development and production of 20,000 tiles could cost as little as the price of the hardware for just one traditional NASA mission. Once development costs are over, producing the resulting Smart Tiles becomes cheap. Because launch costs for over 1,600 EPMFS could come in at a mere $200 million, ten launches could be purchased for $2 billion. Less than the cost of building the Curiosity Mars Rover. Consequently, ten missions could provide the backbone for an energy infrastructure for the solar system. An energy, communications, positioning, and AI-empowered computing system. A system with a swarm intelligence and learning abilities. A system with a group IQ. And arrays of tiles on Mars and the Moon could share data and new insights, new learning approaches, with tile arrays on distant moons, planets, comets, and in intriguing places like the asteroid belt.

But there is also an educational component. High schools and colleges can each adopt their own

EPFMS. And high school and college students can participate in combing through the EPMFS data the way that students flock to crowdsourcing sites like Planet Hunters [1] to comb through astronomical data for signs of planets around distant suns.

Then there's the long-range goal of EPMFS: pre-positioning rocket fuel, water, and breathable oxygen on the Moon and Mars. The sheet batteries at the center of EPMFS are energy-storers. But there is a better way to store energy: use EPMFS electricity to extract the frozen water heaped on crater bottoms at the poles of the Moon; and use it to extract the frozen water within the first three feet of the Martian surface. Employ the electric power of a EPMFS grid to separate those ices into hydrogen, oxygen, and liquid water. Store that hydrogen, oxygen, and water in tanks. And pre-position resources for the first humans to set up a permanent base on the Moon and for the first humans to arrive on Mars. Hydrogen and oxygen are rocket fuel. They can be used to refuel a rocket that is landed on the Moon and prepare it for takeoff back to earth. They can do the same with a vehicle that is landed on Mars.

The Moon is a fabulous resource base. See Figure 3.3. Because that gravity is so low compared to the Earth, hydrogen and oxygen from the Moon's ice can be launched inexpensively from the lunar surface and pre-positioned in fuel depots in space. What is the value of those in-space fuel depots? Imagine a highway without gas stations. It isn't a highway. It is a parking lot for abandoned cars, cars that have run out of gas. Gas stations in space can establish freeways in the sky. They can refuel craft from earth for the long trip to Mars. Or to any other body in the solar system. In-space fuel depots can lay the base for a permanent transportation infrastructure in space. A base for a highway system in the sky. Meanwhile the supplies of drinkable water and breathable oxygen built up using the Smart Tiles' energy supply can make human habitations - Bigelow inflatable habitats, for example - livable.

EPMFS could also play several roles in achieving the scientific goals of NASA's Decadal Surveys:

- Networks of EPMFS seismic detectors can gather planetary science data on the Moon, Mars, Titan, Europa, Venus, or on the Martian moons Phobos and Deimos.
- EPMFS can provide power, visual sensors, chemical sensors, and radio sensors to upcoming small body, comet, and icy body missions (See Figure 3.4). For example, if EPMFS had been included on the ESA's Rosetta mission, the Philae comet lander would never have experienced either a power problem or a communications difficulty.
- Then there is climate observation and atmospheric research via chemical, visual, temperature, barometric pressure, and humidity sensors on Mars, Venus, Titan, and Europa.

Other decadal survey goals to which EPMFS could contribute include:

- A sample return from the south pole of the Moon, where EPMFS could provide power, communications backup, and cloud computing,

[1] http://www.planethunters.org/

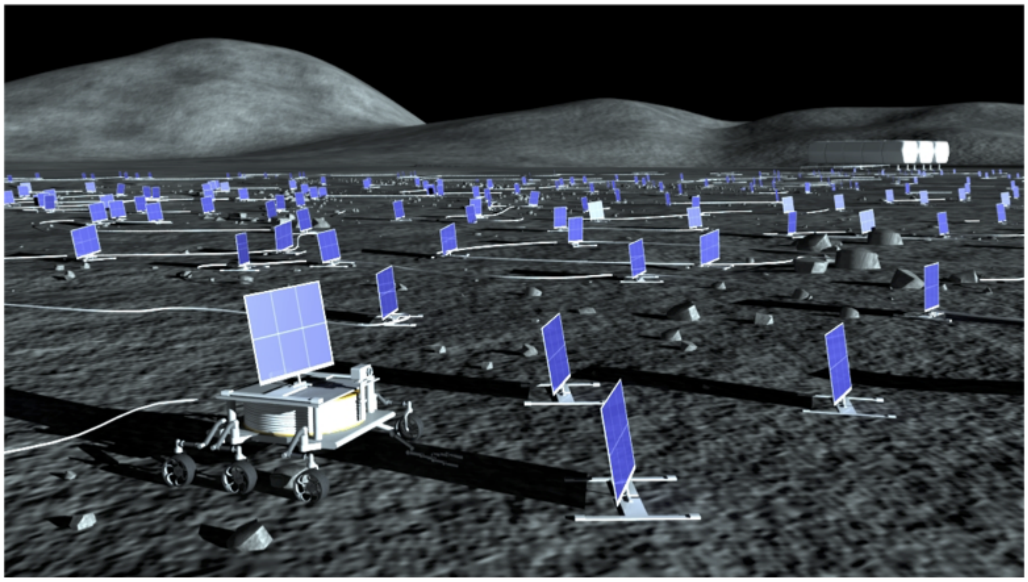


Figure 3.3: EPMFS Tiles customized for the Moon's poles will take off from Earth as flat panels stacked in a SpaceX Dragon capsule. When they hit the lunar surface, they will unfold, using their framework as a stand. Water is located at the lunar poles. The sunlight on those polar surfaces is nearly parallel to the ground. To harvest solar energy, an EPMFS Tile has to stand up. It has to go vertical. Though a rover is shown in this picture positioning the EPMFS tile, no rover is necessary, an an EPMFS array is a self-assembling system. Art: Anna Nesterova.

- A Europa lander: EPMFS can be used on the icy surface of Titan or Europa to provide energy, computing power, communications, and sensor data.
- Planetary defense: EPMFS arrays in LEO and in deep space could power satellites hunting the heavens for incoming asteroids.
- Comet sample returns: EPMFS could contribute power, communications, and brainpower to missions designed to bring scoops of cometary matter to earth.
- And Venus missions: temperature hardened smart tiles could provide seismic information and atmospheric data on the hellish environment of the second planet from the Sun.

But there are yet more customers that could benefit from EPMFS.

- The American military is conscious of the need for a military presence in space that can't be wiped out by anti-satellite weapons. On March 2, 2015, a report commissioned by Congress from the University of California Institute on Global Conflict and Cooperation concluded that Chinese military efforts in space aim to put American communications and GPS satellites out of business in case of a conflict. That would blind the US military. Big, expensive satellites are easy to knock out. But massively distributed systems in the sky cannot be easily destroyed. Wipe out 300 EPMFS tiles in a 1,600 tile array, and you still have 1,300 tiles up, running, sensing, sharing data, and providing communications,

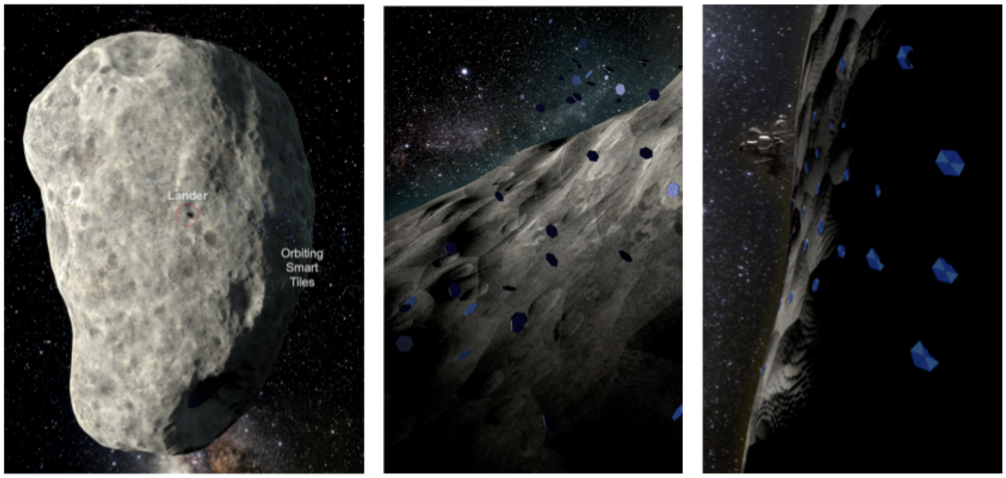


Figure 3.4: How EPMFS Tiles could have saved the Rosetta Mission to Comet 67P Churyumov-Gerasimenko. The Rosetta mission's lander, the Philae, hit the surface of the comet, bounced a kilometer, then landed in the shadow of a cliff. So it went without power and communications for seven months - from November 15, 2014 to June 13, 2015. EPMFS Tiles take up very little space in a nose cone, so they can be packed to accompany a mission like carry-on luggage. When the EPMFS Tiles reach their destination, they can function in two ways: they can be scattered on the surface near the lander but far enough away to maximize their odds of being in sunlight; and if the target body has sufficient gravity, EPMFS Tiles can be placed in orbit. The result: EPMFS Tiles can provide power, communications, and computational power to the mission with or without cliffs and shadows. Art: Chuck Carter.

positioning, and views of the terrain to forces on earth. What's more, EPMFS that are destroyed can quickly and easily be replaced. The EPMFS can form a network in the sky performing many of the functions of traditional GPS and communications satellites. Again, wiping out an array of 1,600 smart tiles is not easy. And eradicating an array of 16,000 is even harder.

- Organizations like the Chinese Academy of Space Technology, Japan's space agency JAXA, and figures like Dr. A.P.J. Kalam, the eleventh president of India and father of India's rocket program, are fierce advocates of harvesting solar energy in space and transmitting it to earth. They argue that we can eliminate mankind's carbon footprint by using space solar power. In fact, they are convinced that space solar power can replace fossil fuels entirely. And they believe that space solar power can provide enough surplus power to run masses of desalination units, thus ending the world's water shortage. That is why the Chinese government, Japan's Mitsubishi, and America's Northrop Grumman have put multi-million dollar investments into space solar power initiatives. Our ion-drive enabled EPMFS can form massive solar arrays for minimal cost. And our EPMFS do not just gather traditional solar energy. They also gather energy from ambient radio waves and from heat differentials.

- The DoD calculates that getting one gallon of gasoline to a conflict zone can cost $400. And, worse, the military loses more men and women trying to supply fuel to conflict zones than in any other mission. EPMFS could beam in power for a fraction of that cost.
- Similarly, supplying power in emergencies - from earthquakes to tsunamis - is expensive. And agonizingly slow. Those afflicted by the catastrophe die from lack of power. EPMFS could beam electricity to these disaster sites.
- The states of California and Washington have mandated that a certain percentage of their power come from renewable resources. The power that EPMFS solar arrays in earth orbit could provide is massively renewable and totally carbon free.
- Asteroid mining companies will need the power EPMFS provide. And they may need EPMFS positioning and computing services. There are currently two serious players in the asteroid mining business - Peter Diamandis' Planetary Resources and Rick Tumlinson's Deep Space Industries. Within less than a decade, these two companies should be active in space. And they will need what EPMFS can deliver.
- If the International Space Station needs power or cloud computing capabilities, EPMFS will be there to provide it.
- XISP's space-to-space power beaming project was initially conceived to beam power from the International Space Station to cubesats, commercial projects, and scientific experiments parked in the vicinity of the ISS. XISP's space-to-space power beaming project could use the power from our EPMFS to service power users in space. In fact, XISP is eager to have EPMFS as a provider.
- Industrial experimenters and processors. An increasing number of industrial processors are eying space. They see the no-gravity environment as a benefit. For example, makers of high-cost, specialized fiber optic cables realize they can produce fiber optics in which crystals do not settle to the bottom of a thread, thus dramatically increasing the fiber optic strand's carrying capacity. These makers are currently testing new fiber-optic production devices in the gravity-less environment of Reduced Gravity Aircraft (vomit comets) with the intention of installing devices like these permanently in the International Space Station. And Made In Space is about to install its second 3-D printer in the International Space Station. Industrial users of space will need more power than the solar panels on the International Space Station can provide. And EPMFS can provide that power.
- NASA rovers on Mars or the Moon could recharge their batteries from the power supply stored by EPMFS. Those wandering vehicles could also get weather reports on upcoming destinations from EPMFS Tiles scattered across the lunar and Martian surface.
- And the oxygen, hydrogen, and liquid water electrolyzed using EPMFS power can supply fuel depots in space, propellant depots that make long trips in deep space an everyday affair. In other words, hydrogen, oxygen, and water extracted with the power provided by EPMFS can fill the tanks of gas stations in space. EPMFS can supply the refueling centers that provide a permanent space transportation infrastructure, the already-mentioned highway in the heavens. The expressway to the planets.

What does this all amount to? EPMFS can provide more than an energy infrastructure for the solar system. See Figure 3.5 and 3.6. They can provide a cerebral cortex for the planets and the moons, a brain in space. But there is more. EPMFS can help turn Homo Sapiens into Homo Coelestus - Earth's first spacefaring species. And they can do it for remarkably small amounts of money.

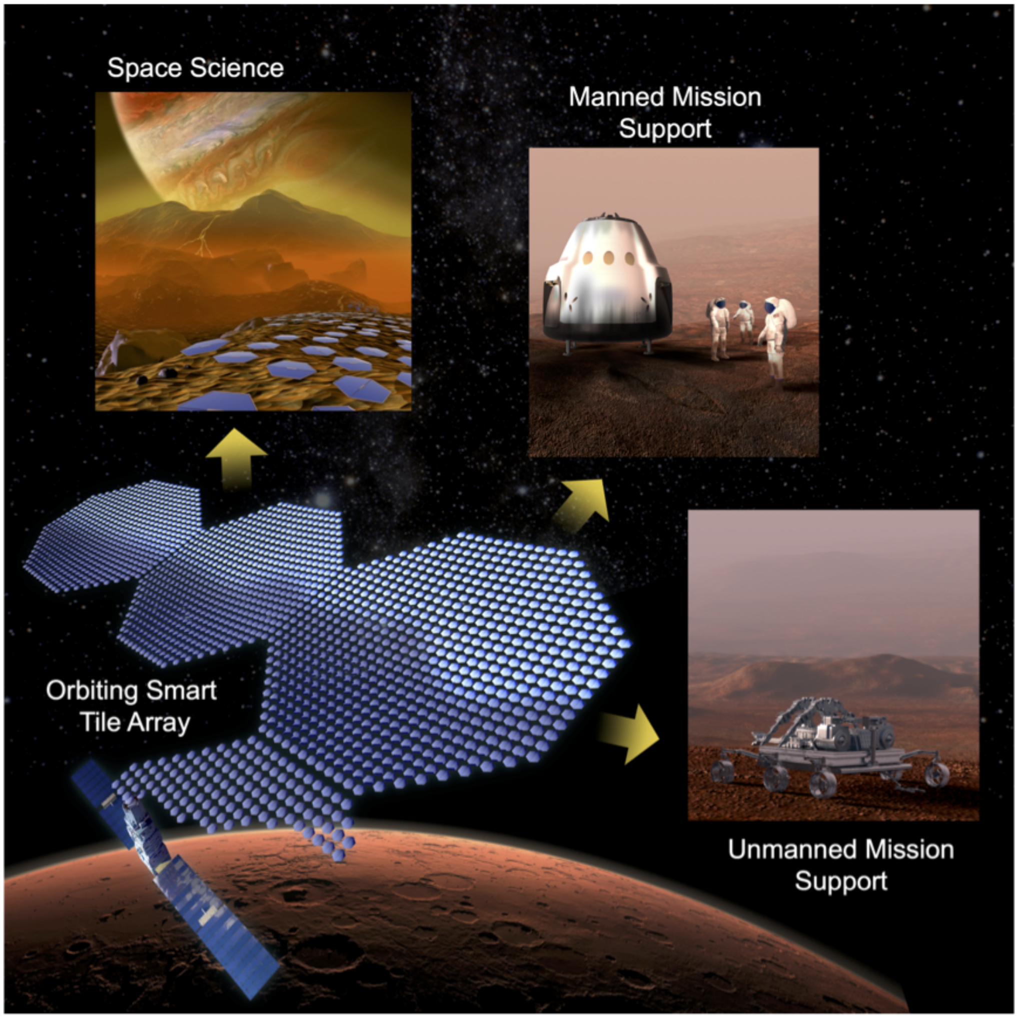


Figure 3.5: Some of the many uses of EPMFS in Space Exploration. Art: Chuck Carter.

3.4 Study Conclusions and Plan Forward

This report described the work done during the Adaptive Multifunctional Systems for Micro-climate Control Study held at the Caltech Keck Institute for Space Studies in 2014-2015. Dr. Marco Quadrelli (JPL), Dr. James Lyke (AFRL), and Prof. Sergio Pellegrino (Caltech) led the Study. The Study included two workshops, one in May 2014, another in February 2015. This report is

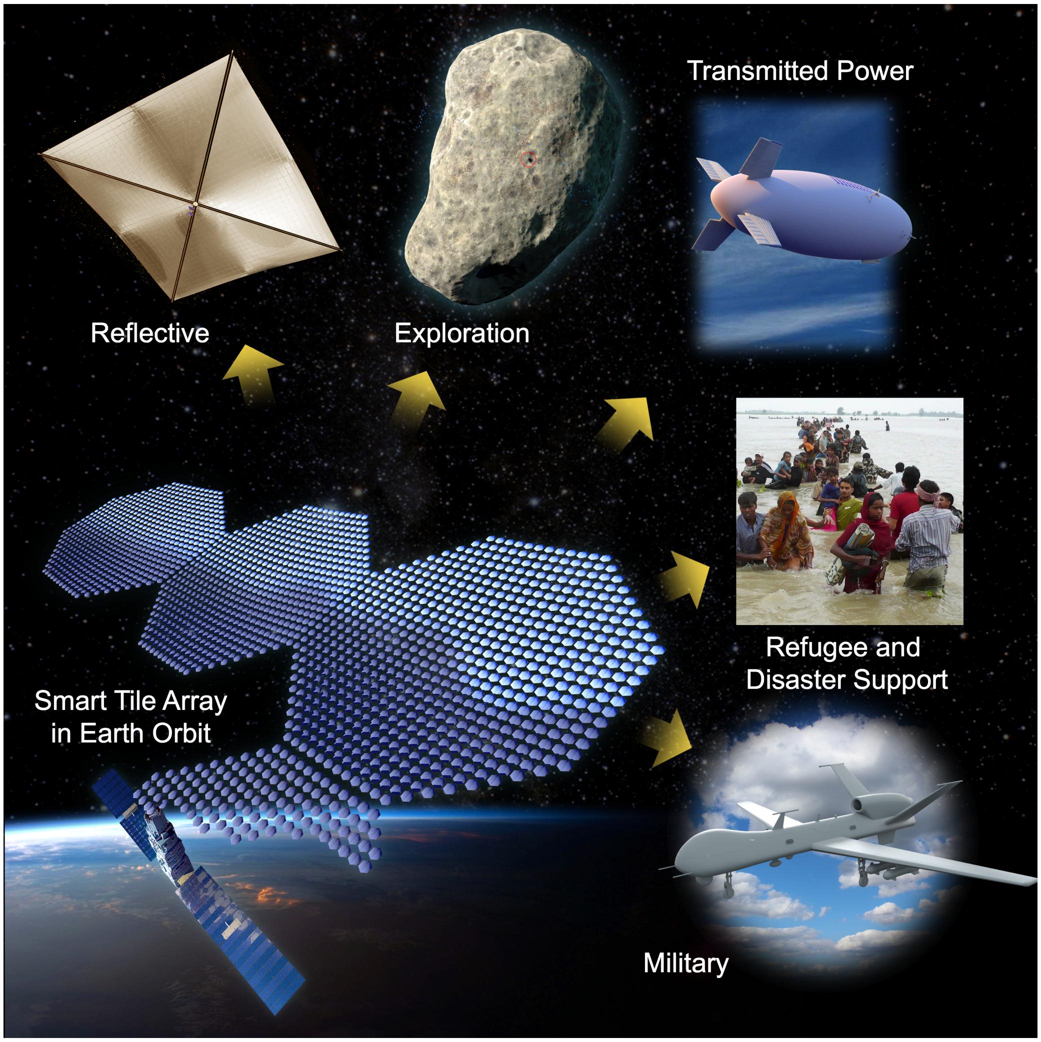


Figure 3.6: Some of the many uses of EPMFS with benefits to the civilian sector. Art: Chuck Carter.

the final report of the Study and describes the potential relevance of adaptive multifunctional systems for microclimate control to the missions outlined in the 2010 NRC Decadal Survey.[2]

The technical goal of the Study was to identify the most efficient materials, architectures, structures and means of deployment/reconfiguration, system autonomy, and energy management solutions needed to optimally harvest energy around space assets in extreme environments (EE). This novel solution is called an energy-projecting multifunctional system (EPMFS). For example, compact packed thin-layer reflective structures unfolding to large areas can reflect solar energy, warming and illuminating assets such as exploration rovers on Mars or human habitats on the

[2]Committee on the Planetary Science Decadal Survey, National Research Council of the National Academies, Vision and Voyages for Planetary Science in the Decade 2013–2022, National Academies Press, Washington, DC, 2011.

Moon. Several technology disciplines are involved in this challenge: distributed architectures, multifunctional systems, extreme environments, energetics, and system autonomy. Among these, the Study has identified three critical technology areas that would enable an energy infrastructure capable of supporting new challenging planetary science missions in EE. The first area is **hybrid solutions for energy harvesting**, in which energy gathered via solar collection/concentration using photovoltaic elements is beamed via microwaves to an in-situ thermoelectric conversion element, with energy storage capability. The second area is the paradigm of **distributed cellular architectures**, in which multiple intelligent nodes (each node a highly compact unit integrating multiple sub-functions such as power, communication, computing, energy-harvesting) are part of a scalable network architecture that could take the form of a "fabric-sat," compactly stowed and deployable to a large area. The third area is **multifunctional and reconfigurable systems**, which combine the versatile actuation capability of intelligent materials (electro-active polymers, photo-strictive, piezoelectric, magnetostrictive) to realize foldable and deployable two-dimensional flexible electronic devices with geometric morphing capabilities which, as they harvest energy at the nodes, can also operate as a reconfigurable electromagnetic aperture of large area, leading to high data rate communication at varying bandwidths.